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Local buckling coefficient for cold-formed steel Sigma sections

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Abstract. Cold formed steel profiles (CFS's) allow the use of a variety of cross-sections, due to the flexibility of manufacture and assembly. The use of CFS's is generally associated with slender structural designs, with a large ratio between the width and thickness of the members that compose its cross-section, which makes the profiles lighter and more economical. CFS's are susceptible to instability due to the slenderness. This phenomenon induces problems such as the local buckling of their members when subjected to compression. The design of these profiles is approached by the Brazilian standard, and one of the calculation procedures presented is the Effective Section Method (ESM), which considers local buckling through effective geometric properties of the cross-section. For this purpose, the standard defines the buckling coefficient of the complete section by means of formulations for specific profile types. In order to define a specific formulation for different cross-sections, it is necessary to perform particular analyzes, such as numerical simulations using Finite Element Methods (FEM) or Finite Strip Methods (FSM). Therefore, this work aims to define a formulation for the buckling coefficient of the complete section of a Sigma profile, which is not defined in the scope of the Brazilian standard. For this, a numerical analysis was developed using the ABAQUS finite element software. A parametric study was conducted through a range of several Sigma profile's dimensions submitted to uniform compression. Based on the determinations of critical buckling stresses from numerical analysis, a satisfactory formulation was developed. Furthermore, relevant data about the study of local buckling behavior of Sigma-type has been determined and can be useful for their design.

Keywords: cold-formed profiles; effective section method; local buckling coefficient.

1 Introduction

Cold formed steel profiles are used in civil construction in structural systems, presenting characteristics such as high ratio between the resistant capacity and its weight, wide versatility and variability in the design of cross-sections. In addition, CFS's are easy to handle and transport, providing an agile assembly compared to other systems. However, these profiles are highly susceptible to instability phenomena associated with low thicknesses, which can occur locally (local buckling and distortion), global mode (flexural, torsional or flexural-torsional) or even mixed-mode, characterized by the interaction of the local and global modes.

The Brazilian standard ABNT NBR 14762: 2010 [1] provides three methods for CFS's design, the Effective Width Method (EWM), the Direct Strength Method (DSM), and the Effective Section Method (ESM). In the ESM, local buckling is considered through the effective properties determined based on the geometry of the section as a whole. Thus, it is necessary to calculate the local buckling coefficient for the complete section (kl), which has a specific formulation for different cross-sections. Sigma profiles are not approached in Brazilian standard and are studied in this paper, emphasizing the importance of the limitations of the theoretical model as mentioned [2].

2 Theoretical foundation

Considering the three calculation methods present in the ABNT NBR14762: 2010 [1] standard, it is found that in the EWM the members of the profile are considered singly, determining effective sections properties [3]. Grigoletti [4] affirms this procedure consists of decreasing the widths of the members through formulas theoretically deduced and calibrated experimentally. The effective widths are used to determine the new geometric properties of cross-section.

Regarding the DSM, the cross-section is treated as a whole, using strength curves verified experimentally for the calculations [5]. Santos *et al.* [6] explain that in ESM the local buckling is considered from the effective (reduced) geometric properties of the complete cross-section. In other words, Rocha *et al.* [7] assert that in ESM, to design the cold-formed profiles under compression and flexural, the geometric properties of the effective section are used directly.

In the latter method (ESM), the axial strength of local buckling (N_l) is calculated by means of elastic stability analysis or directly by the eq. (1). According to Batista [8], as this procedure is based on the real thin-walled buckling behavior, important improvements can be obtained in regard to the EWM. Furthermore, Costa [5] mentions the ESM has advantages over the DSM, once the strength axial values of local elastic buckling can be obtained directly:

$$N_l = k_l \times \frac{\pi^2 \times E}{12 \times \left(1 - \nu^2\right) \times \left(b_w / t\right)^2} \times \mathrm{A}. \tag{1}$$

Where: k_l is the local buckling coefficient; E is Young's modulus; A is the gross cross-sectional area; v is the Poisson's ratio; b_w is the nominal width; e t is the thickness.

Formulations for calculating the local buckling coefficient (k_l) in 4 sections types of CFS's are presented by the Brazilian standard ABNT NBR 14762: 2010 [1], which are: (a) U and Z sections; (b) U and Z stiffened and top hat; (c) rack section; and, (d) rectangular tubular section. These equations were developed from studies in the literature and are described according to a parameter called η, which corresponds to the b_f / b_w ratio, in a range from 0.1 to 1.0 and bf is the nominal width of the flange.

For other sections, no equations are presented to determine this coefficient. Therefore, computer programs based on numerical methods, such as FEM and FSM can be used to determine the local elastic buckling modes replacing the critical load in the eq. (1). ABAQUS [9] is a software that can simulate the behavior of profiles from a FEM analysis and, then it is possible to obtain formulations for the local buckling coefficient of specific profiles using the critical strength. Whereas, CUFSM [10] is a software based on the FSM for the study of cold-formed profiles. According to Brandão *et al.* [11], the main advantage of CUFSM is the possibility of interaction between local and global buckling in a unique equation.

3 Numerical Analysis

With the aim to simulate the local buckling of the Sigma profile, a FEM analysis was conducted using the ABAQUS software [9]. Therefore, important considerations were adopted in order to the numerical models accurately reproduced the real behavior of the Sigma cross-section. By means of a parametrical study, a formulation was proposed to define the local buckling coefficient (k_l) for the Sigma profile, submitted to uniform compression. An elastic buckle analysis was developed, which results in buckling modes, through the solution of a problem of eigenvalues and eigenvectors. These values represent the critical buckling loads associated with buckling modes. In this analysis, the Young's modulus (E) was adopted equal to 200 GPa and 0.3 for the Poisson's ratio.

3.1 Numerical models geometry

This study is composed of 600 models, whose denominations of the lengths of the cross-section are presented in Fig. 1. The parametric analysis was performed considering the variation of cross-section total height, of the b_2/b_1 ratio, and of the thickness. The length b_1 was calculated according to the prior determination of the total height, the vertical dimensions b_5 and b_6. In order to obtain an overarching formulation, models with 15 different heights were simulated and for each one, 10 ratios between b_2 and b_1, and 4 thickness were considered resulting in 600 models. To enable the study of the thickness influence (t) on the Sigma section local behavior, this analysis presents four variations of t, is equal to 1.5 mm, 2.0 mm, 2.5 mm and 3.0 mm. Through the validation of the models with CUFSM, the least critical load of the occurrence of local buckling occurred for values close to the web length. In this sense, values corresponding to the width of the web were adopted as the profile length. To extract only results related to the local buckling, only small-sized profiles, with length equal to the member b_1 were considered, whereas it is the member responsible for the beginning of the buckling. Table 1 shows the variation of the dimensions adopted, as well as the lengths considered fixed.

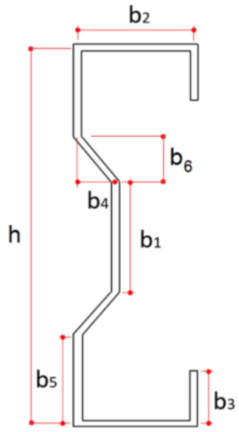

Figure 1. Sigma cross-section.

Table 1. Parameters used in numerical analysis.

Parameters	Adopted variation
Total height (mm)	160; 170; 180; 190; 200; 210; 220; 230; 240; 250; 260; 270; 280; 290; 300
Length (mm)	b_1
Thickness (mm)	1.5; 2.0; 2.5; 3.0
b_2/b_1	0.1; 0.2; 0.3; 0.4; 0.5; 0.6; 0.7; 0.8; 0.9; 1.0
b_3 (mm)	12.5
b_5 (mm)	34.0
b_4 (mm)	20.0
b_6 (mm)	21.0

3.2 Mesh definition

Quadrilateral shell elements with 4 nodes, with full integration (S4) and reduced integration (S4R) were adopted to discretize the profiles, whose dimensions width and height are greater than the thickness. Due to the larger computational power of the S4 element than S4R element and results with negligible differences between both, it was decided to use the reduced integration in the analyzes. A mesh convergence study was conducted to attest the efficiency of the results and it was noted that elements below 5.0 mm did not have significant differences in the results, thus, a mesh with elements of 5.0 mm was adopted.

3.3 Boundary and load conditions

To represent the uniform compression behavior, a unitary load was applied in the geometric center of the cross-section and a coupling type interaction were considered to distribute the force along the section. This was performed in order to all members presented the same displacements and rotations in the direction of the load application and the same displacements in the other directions, therefore, the occurrence of eccentricities in the use of distributed load was identified. Furthermore, boundary conditions were applied in reference nodes corresponded to the geometric center by using the coupling restriction. In the opposite section of the applied load, displacements and rotations were restricted in the longitudinal axis and displacements in the other directions. On the other side of the cross-section, rotations in the load direction and displacements in the other two directions were restricted. The load application and the boundary conditions are shown in Fig. 2.

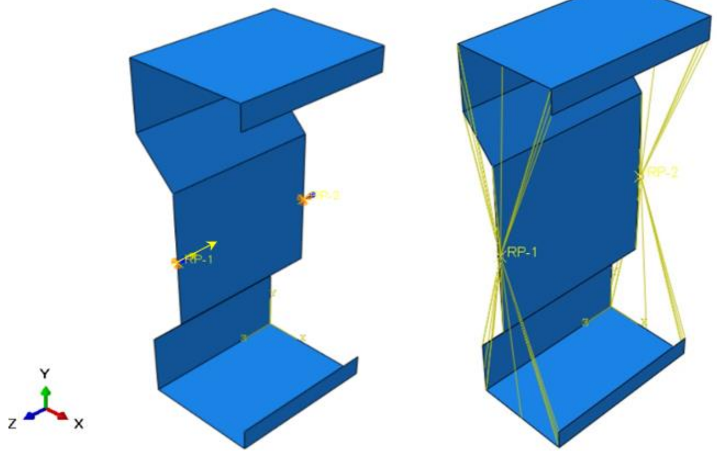

Figure 2. Load application and the coupling condition.

3.4 Numerical model validation

The validation began by verifying a stiffened U-profile, which has a coefficient well determined by ABNT NBR 14762: 2010 [1]. Through the software ABAQUS [9] and CUFSM [10], critical force values were found with variations below 1% in relation to the normative values, for the boundary conditions adopted and length equal to web height. Subsequently, with these boundary conditions properly calibrated, it was started to validate the profile under study. Previously, the Sigma cross section was modeled in the CUFSM software, being possible to find length values that resulted in local buckling, in addition to the corresponding critical forces.

Two models with thickness equal to 1.5 mm were used for validation with CUFSM [10]. The first has a height equal to 200 mm and a ratio b_2/b_1 equal to 0.7 (Model 1) and the second has a height and relation b_2/b_1 equal to 300 mm and 0.1, respectively (Model 2). The validation results are shown in Tab. 2 and their respective buckling modes are shown in Fig. 3 for Model 1. Comparing the results obtained, differences of 1% and 2% were observed for models 1 and 2, respectively.

Table 2. Results obtained from numerical validation in the CUFSM program.

Model	N_{cr} ABAQUS (kN)	N_{cr} CUFSM (kN)	Difference (%)
Model 1	158.07	159.18	-1
Model 2	405.52	398.08	2

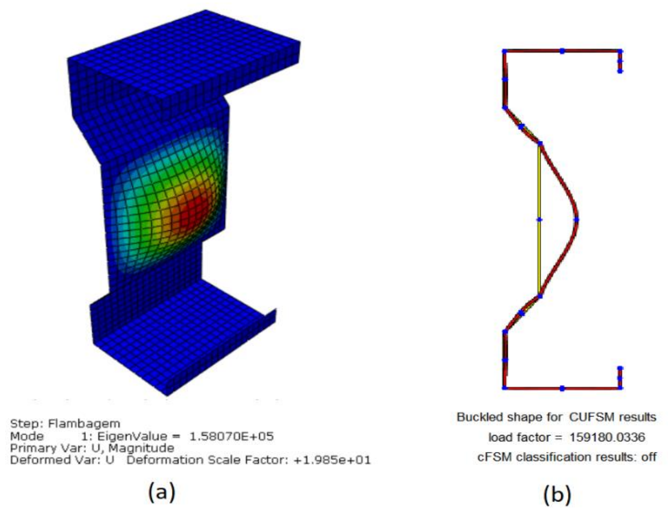

Figure 3. Buckling modes comparison: (a) ABAQUS; (b) CUFSM.

4 Results

To purpose a formulation describing the local buckling coefficient for Sigma sections, the influence of the ratios b_2/b_1, b_4/b_1 and thickness were evaluated. The analyses are shown in Fig. 4, 5 and 6.

To evaluate the influence of b_2/b_1 on k_l values, the thickness was fixed and an approximately constant behavior was identified (Fig. 4), with differences around 1% between the extreme values and the mean value, for each web height.

The ratio b_4/b_1 is relevant to determine the local buckling coefficient (Fig. 5), indicating an analogous relation with the b_2/b_1 x k_l for the profiles approached in ABNT NBR 14762:2010 [1], which can be justified since the inclined element performs a support function for the element susceptible to buckling (b_1), according to Fig. 3. The figure also shows a tendency of overlapping curves for different b_2/b_1 values, reinforcing the non-influence of this ratio to determine k_l.

It was analyzed the thickness variation on the local buckling coefficient values for each web height (Fig. 6). It was verified a slight influence of the thickness, once the thickness increases the k_l decreases. However, due to the limited amount of thickness and its low influence on the behavior of k_l, a relation with this parameter was not considered.

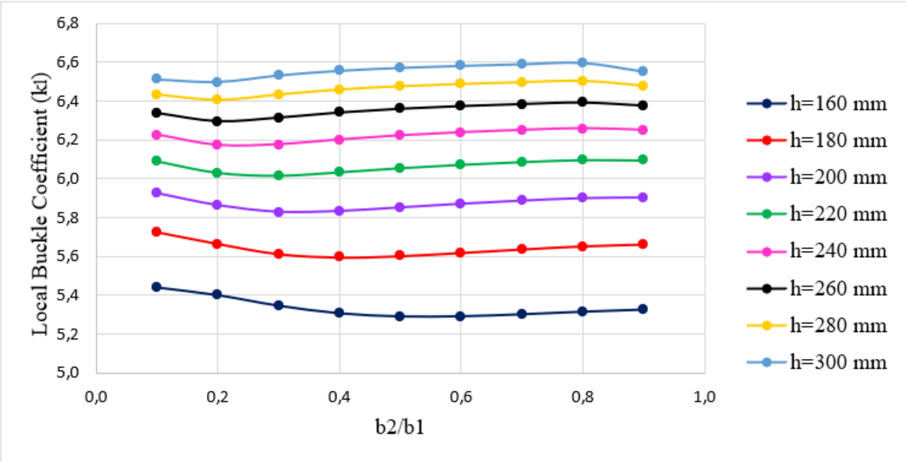

Figure 4. Local Buckle Coefficient as a function of the ratio b_2/b_1.

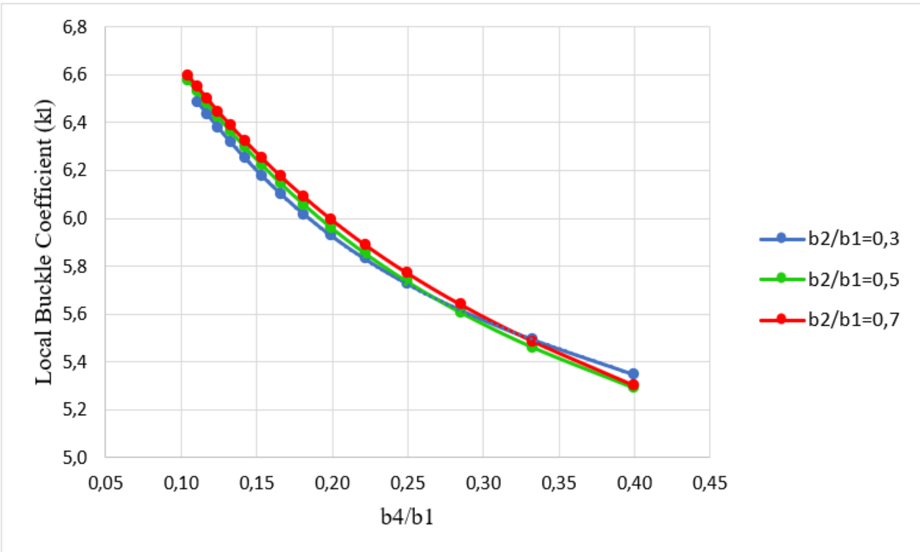

Figure 5. Local Buckle Coefficient as a function of the ratio b_4/b_1.

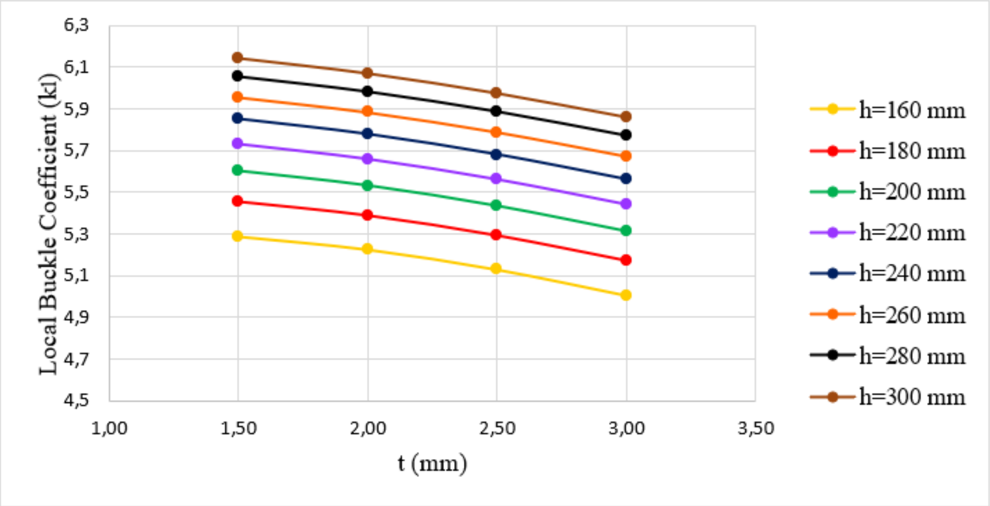

Figure 6. Local Buckle Coefficient as a function of the thickness.

The results demonstrate that the ratio b_2/b_1 is not a relevant parameter to define a formulation and describe the local behavior of the Sigma section with the central element susceptible to local buckling. Therefore, the eq. 2 was proposed as a third-degree polynomial function of the variable b_4/b_1 and it is valid for the range $0.1 \leq b_4/b_1 \leq 0.4$. The linear correlation coefficient (R^2) obtained was 0.867. Figure 7 illustrates the curve obtained from the numerical study and shows that larger ratios of b_4/b_1 leads to smaller values of the local buckling coefficient.

$$k_l = -14.22\left(\frac{b_4}{b_1}\right)^3 + 17.93\left(\frac{b_4}{b_1}\right)^2 - 10.18\left(\frac{b_4}{b_1}\right) + 7.39. \quad (2)$$

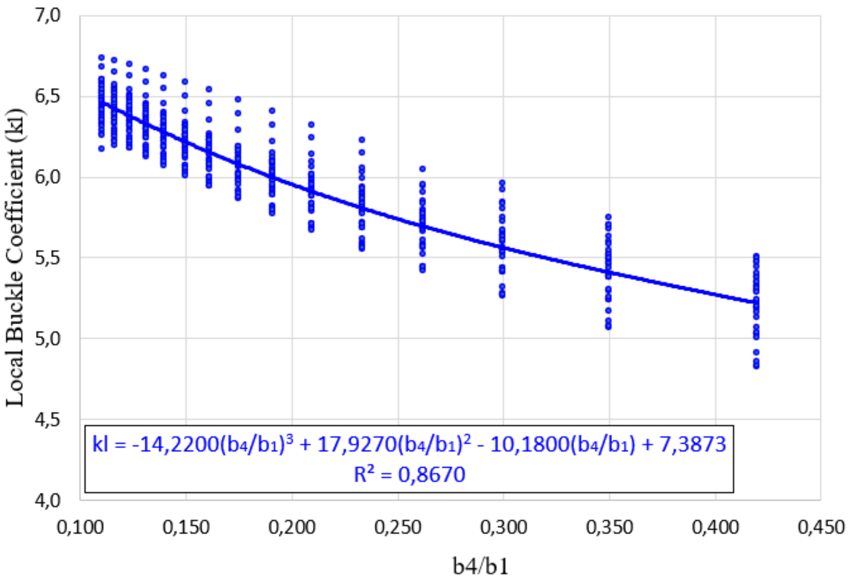

Figure 7. Formulation of Local Buckle Coefficient as a function of the ratio b_4/b_1.

5 Conclusion

Through a parametric analysis considering different dimensions of the Sigma profile member, an equation was defined based on the b_4/b_1 ratio. This equation is applicable to Sigma profiles with studied behavior patterns, in which the central element is susceptible to local buckling. Furthermore, the curve is valid for a fixed dimension of the inclined element.

In the study presented, it was found that the thickness has little influence on the behavior regarding the local buckling coefficient of the Sigma profile. In addition, due to the thickness range adopted in the models, a pattern of influence on the k_l behavior cannot be established. Moreover, for this study, it was also identified that the b_2/b_1 ratio does not present much impact, unlike the profiles approached in ABNT NBR 14762: 2010 [1]. This can be explained because of the web support that is supplied by the inclined element in the Sigma profile.

The b_4/b_1 ratio proved to be a major factor in defining the section buckling coefficient. It is important to emphasize that Sigma profile has a complex geometry and further studies are needed to verify the influence of the parameters not varied in this study. In addition, it is also necessary to analyze cases in which local buckling can occur at height b_5, when this element is heigher than b_1.

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