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Axial compression resistance of cold-formed steel lipped channel at elevated temperatures

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Abstract
In the present study, it was analyzed analytically and numerically the variation of the yield strength reduction factor for sections subject to local buckling at high temperatures, $k_{\sigma,\theta}$, as a function of the relative slenderness λ_p for U lipped channel profiles. The analytical models used are based on the European Prestandard EN 1993-1-2:2005 and the Brazilian Standard ABNT NBR 14323:2013. The numerical model is based on the Finite Element Method. It was verified that these numerical results differed from standard analytical results. Theoretical values of an adjusted reduction factor showed a correlation with the relative slenderness of the cross section.

1. Introduction

The cold-formed sections, being made of thin plates, are subject to phenomena of local instability, such as local and distortional buckling. In a fire situation, the knowledge of the behavior of these profiles, especially in relation to the instabilities, is still early and therefore further studies are needed.

Because of these instabilities phenomena, the light gauge steel profiles reach the critical load before yielding, preventing the use of the reduction factor for the yield strength of steel at elevated temperature, $k_{y,\theta}$, which is defined at total strain of 2% in the steel stress-strain curve at high temperatures.

Nowadays, the European Prestandard EN 1993-1-2:2005 and Brazilian Standard ABNT NBR 14323:2013 propose to use the reduction factor $k_{\sigma,\theta}$ for design profiles subject to local buckling, defined to a residual strain of 0.2%. Fig. 1 shows the variation of this factor, as well as the reduction factor $k_{y,\theta}$ and the reduction of elastic modulus, $k_{E,\theta}$, as a function of the steel temperature.

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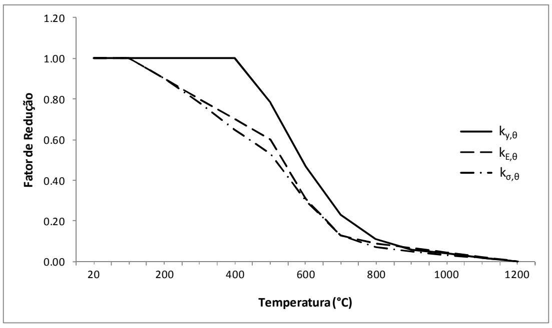


Figure 1: Variation of reduction factors $k_{y,\theta}$, $k_{\sigma,\theta}$ and $k_{E,\theta}$ as a function of steel temperature (EN 1993-1-2:2005)

In that way, for profiles subjected to local buckling, i.e., with critical local buckling stress below the yield stress, we use the reduction factor $k_{\sigma,\theta}$; otherwise we use $k_{y,\theta}$. The $k_{\sigma,\theta}$ and $k_{y,\theta}$ ratio can reach values of 0.65 and, according to EN 1993-1-2:2005 and ABNT NBR 14323:2013, the reduction factor $k_{\sigma,\theta}$ should be used even when the critical local buckling stress is slightly lower than the yield strength.

It is easily noted, as stated by these normative specifications, a discontinuity in the treatment of local buckling phenomenon in fire situation, since it uses the reduction factor $k_{\sigma,\theta}$ in profiles where local buckling occurs before the material reaches its yield strength and the reduction factor $k_{y,\theta}$ otherwise. It is important to note that the reduction factor $k_{\sigma,\theta}$ is used even if the local buckling occurs at the limit of yielding.

The aim of this study is to analyze the theoretical variation of the reduction factor $k_{\sigma,\theta}$ in relation to the relative slenderness for U lipped channel profiles. To conduct this study, many of these profiles, provided in Brazilian Standard ABNT NBR 6355:2003, were analyzed numerically for temperatures of 20°, 400°, 550° and 700° C.

2. Analytical Model

There are three methods in Brazilian Standard ABNT NBR 14762:2010 to calculate the design resistance at room temperature: Effective Width Method (EWM), the Effective Section Method (ESM) and the Direct Strength Method (DSM).

The EWM consider the elements of the cross-section as isolated plates, calculating the effective width for each element separately. In another way, the ESM and the DSM consider the behavior of the whole section, through a relative slenderness associated to the profile cross-section,

$$\lambda_p = \sqrt{\frac{\chi A f_y}{N_l}} \tag{1}$$

where: χ is the reduction factor for global buckling; A is the gross cross-sectional area; f_y is the yield strength; N_l is the critical axial load for local buckling.

In the DSM, the critical local buckling load, N_l is normally obtained by a analysis based on the elastic stability theory, which can be accomplished via computer programs. Using the ESM, for U lipped channel profiles, the critical load can be determined by the equation

$$N_l = k_l \frac{\pi^2 E}{12(1-\nu^2)(b_w/t)^2} \tag{2}$$

where

$$k_l = 6{,}8 - 5{,}8(b_f/b_w) + 9{,}2(b_f/b_w)^2 - 6{,}0(b_f/b_w)^3 \tag{3}$$

k_l is a coefficient associated to local buckling of the cross-section. In the above equations: b_w is the nominal web width; b_f is the nominal flange width; t is the plate thickness.

In a fire situation, the EN 1993-1-2:2005 and the ABNT NBR 14323:2013 allow to perform the calculations of the effective area in the same way as it is done at room temperature, with material properties at 20° C. As shown in Fig. 1, the ratio value between the reduction factors $k_{\sigma,\theta}$ and $k_{E,\theta}$ is close to 1, which justifies the approach adopted by the standards. The design resistance to axial forces of the cross-section for uniform compression at elevated temperature is given by:

$$N_{c,Rd} = \chi_{fi}\, k_{\sigma,\theta}\, A_{ef}\, fy \tag{4}$$

where: χ_{fi} is the reduction factor for global buckling in the fire design situation; A_{ef} is the effective area; f_y is the yield strength.

Since the goal of this work is just to study the phenomenon of local buckling, global buckling-related effects were eliminated by taking χ_{fi} equal to unity.

3. Numerical Model

The profiles were modeled by Finite Element Method (FEM) on the computer program Abaqus (*Simulia*, 2010), using quadrilateral shell elements of 4 nodes with reduced integration. The mesh was refined until they reach an appropriate convergence results. The use of reduced integration did not lead to convergence problems and achieved adequate results, beyond the fact that reduces processing time. The boundary conditions used for these models were doubly pinned supported with a rigid body in the ends.

Firstly, it is necessary to determine the cross-section critical load for local buckling subjected to a concentrated load applied on its geometric center. Afterward, the displacements of the local buckling mode configuration, Fig. 2, was applied as a small initial imperfection to the profile with a maximum value equal to $b_w/1000$, as b_w being the nominal web width.

To determine the ultimate load, it is performed a non-linear analysis with increments of load and displacement. With the intention to minimize the effects of the global buckling was adopted a profile length equal to twice the nominal web width.

The nonlinearity of the material was implemented by means of a steel stress-strain curve, varying with the temperature according to EN 1993-1-2:2005.

To validate the numerical model, the results were compared with the experiments performed by Hanya and Kanno (2010), who analyzed the cold-formed profiles with different types of steel. The characteristics of these profiles and the ultimate loads obtained experimentally by Hanya and Kanno (2010) for various temperatures, $N_{u,e}$, and the numerical results obtained in the present work, $N_{u,n}$, are shown in Table 1. In the first column of Table 1, the profiles are named as follows: b_w (nominal web width) x b_f (nominal flange width) x c (width of the flat portion of the lip) x t (nominal plate thickness).

It is observed that the ratio between the experimental and numerical results, $N_{u,e}/N_{u,n}$, varies from 0.87 to 1.16, proving the efficiency of the numerical model used in this work.

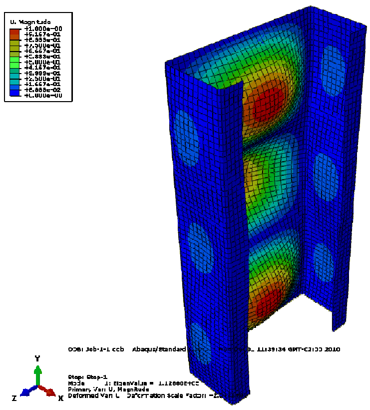


Figure 2: Local Buckling Mode

Table 1: Numerical Model Validation: experimental and numerical results.

Perfis	20°C			350°C			550°C		
	$N_{u,e}$	$N_{u,n}$	$N_{u,e}/N_{u,n}$	$N_{u,e}$	$N_{u,n}$	$N_{u,e}/N_{u,n}$	$N_{u,e}$	$N_{u,n}$	$N_{u,e}/N_{u,n}$
89x44.5x12x1.0	43,2	46,8	0,92	29,7	25,6	1.16	19,2	19,8	0,97
50x44.5x12x1.0	42,2	47,3	0,89	30	25,8	1,16	21,1	19,3	1.09
150x75x12x1.0	40,9	46,6	0,88	31,3	28,7	1.09	22,1	23,9	0.92
89x44x12x1.58	73,3	80,4	0,91	56,2	48,2	1,17	36,7	33,2	1,10
89x44x12x1.57	74,1	85,2	0,87	64,7	61,8	1,05	45,5	44,9	1,01

Additionally, the results at room temperature, obtained by the Effective Width Method (EWM), according to ABNT NBR 14762:2010, were compared with numerical results obtained by Finite Element Methods (FEM). The results, shown in Fig. 3, were obtained ranging the web width from 75 mm to 140 mm, as presented by ABNT NBR 6355:2003. There is a good approximation of the results, noting that the analytical values obtained via MLE are slightly lower than the numerical values. The same profiles were used in the study at elevated temperature as described below.

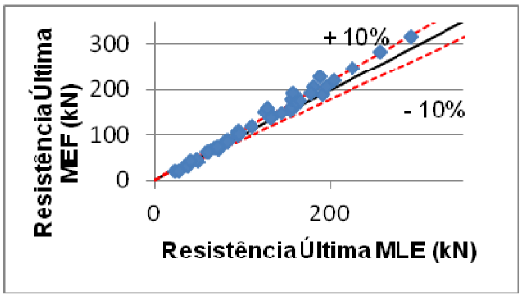


Figure 3: Comparison for the ultimate resistance results obtained via MLE and MEF at 20° C.

4. Results

With the validated numerical model, the studied profiles were chosen with web width ranging from 75 mm to 140 mm, provided by ABNT NBR 6355:2003 [3]. These profiles are consistent with the specifications of ABNT NBR 14762:2010, aiming to not present any distortional or global buckling, as shown in the previous sections. It was found that the numerical results differed from results obtained with the analytical models prescribed by EN 1993-1-2:2005 and the ABNT NBR 14323:2013, who consider $k_{\sigma,\theta}$ varying only with temperature. Based on this observation, theoretical values were determined for the yield strength reduction factor of sections subject to local buckling, $k'_{\sigma,\theta}$, which turns the analytical results closer to the numerical results, using the expression

$$k'_{\sigma,\theta} = \frac{N_{u,n}}{A_{ef}\, f_y} \tag{5}$$

where $N_{u,n}$ are the ultimate loads obtained numerically via FEM, and A_{ef} is the effective area calculated at room temperature, as proposed by the design rules in fire condition.

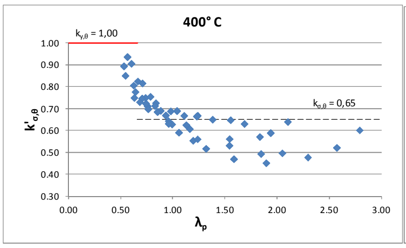
Fig. 4 (a), (b) and (c) show the theoretical variation of $k'_{\sigma,\theta}$ as a function of the cross-section relative slenderness for profiles analyzed according to the methodology presented at temperatures of 400° C, 550° C and 700° C respectively.

The relative slenderness was calculated with Equations 1, 2 and 3. Also it was found that, although not shown in this paper, the numerical values for the critical local buckling load results are very close to analytical results.

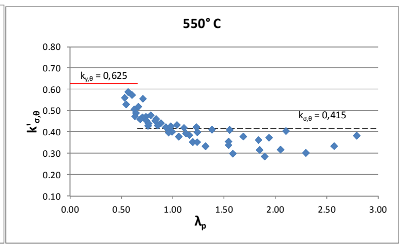
The coefficient values, $k_{\sigma,\theta}$ and $k_{y,\theta}$, according to EN 1993-1-2:2005 and the ABNT NBR 14323:2013, equal in both standards, are indicated in the graphs (Fig. 4) by continuous and dashed horizontal lines, respectively.

As shown in Fig. 4 (a), (b) and (c), it is noted a variation for the reduction factor $k'_{\sigma,\theta}$ differently than proposed by the EN 1993-1-2:2005 and ABNT NBR 14323:2013, which is constant and only dependent of temperature.

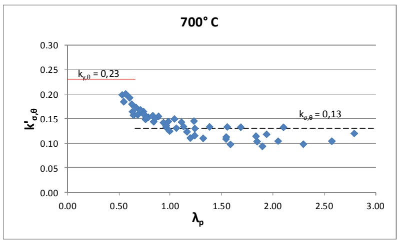
The theoretical reduction factor $k'_{\sigma,\theta}$ tends to the value of $k_{y,\theta}$ as smaller is the section relative slenderness, and decays for larger slenderness values, apparently tending to a constant value on average, which is lesser than $k_{\sigma,\theta}$.



(a)



(b)



(c)

Figure 4: Variation of the theoretical $k'_{\sigma,\theta}$ reduction factor as a function to the cross-section relative slenderness in high temperatures: (a) 400° C, (b) 550° C (c) 700° C.

It is noted that the reduction factor $k'_{\sigma,\theta}$ has a greater dispersion of the results when slenderness increases. To better model this equation, it was analyzed separately in groups of profiles with the same b_w / b_f relationship, where b_f is the nominal flange width and b_w is the nominal web width.

As shown in Fig. 5, the variation of $k'_{\sigma,\theta}$, analyzed separately in groups of profiles, becomes more standardized, i.e., with lesser dispersions. It may be noted that the profiles with b_w / b_f ratio closer to 1.00 have a more pronounced decrease of the $k'_{\sigma,\theta}$ value as slenderness increase, while the profiles with higher b_w / b_f ratio tends to remain constant, more close to the value proposed by EN 1993-1-2:2005 and ABNT NBR 14323:2013. The same behavior occurs in the other temperatures.

Values of b_w / b_f ranging from 1 to 3.5 corresponds to values of b_f / b_w ranging from 1 to 0.28. With a parametric analysis using the Finite Element Method, when only local mode is triggered, it is possible to prove that, for U lipped channels profiles, the local buckling coefficient k_l in U lipped channel sections subjected to uniform compression varies from a lower (at $b_f / b_w = 1$) to a higher value (at $b_f / b_w = 0.28$) , thereby resulting in , respectively, lower and higher values for critical local buckling load, N_l, according to Rodrigues (2004) .

Approaching the theoretical reduction factor as an exponential function (Equation 6) dependent of the cross-section relative slenderness λp, for each profile group separately, it is possible to have a very similar behavior.

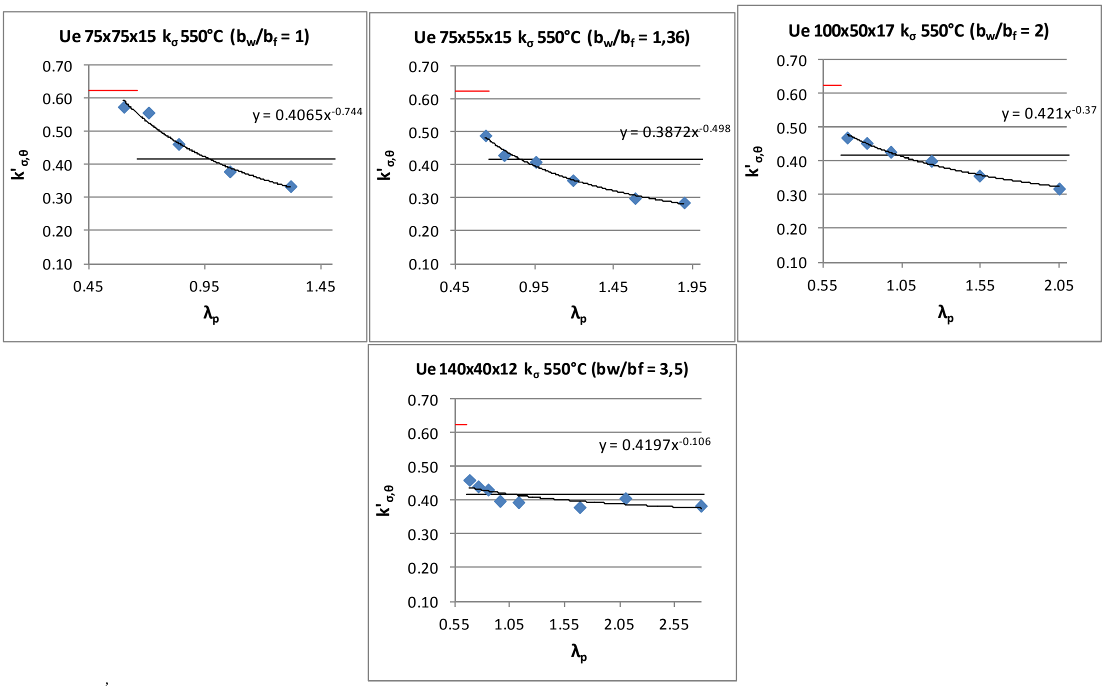


Figure 5: $k'_{\sigma,\theta}$ coefficient variation in relation to the relative slenderness separated in b_w / b_f ratio groups at a temperature of 500 ° C.

$$k''_{\sigma,\theta} = a\lambda_p^b \tag{6}$$

It was conducted a regression analysis with Excel Office 2007 package. In each group is noted that the coefficient "a" of Equation 6 has a value close to $k_{\sigma,\theta}$ proposed by EN 1993-1-2:2005, and the value of the coefficient "b" varies with b_w / b_f (Fig. 6).

After these analysis, it was proposed the equation 6 to calculate the yield strength reduction factor for U lipped channel profiles subjected to local buckling in fire condition ($k''_{\sigma,\theta}$) as a function of the relative slenderness of the profile:

$$k''_{\sigma,\theta} = k_{\sigma,\theta}\lambda_p^b \tag{7}$$

where: $k''_{\sigma,\theta}$ is the adjusted yield strength reduction factor for profiles subjected to local buckling at elevated temperature, as proposed in this work; $k_{\sigma,\theta}$ is the yield strength reduction factor for profiles subjected to local buckling at elevated temperature presented by EN 1993-1-2:2005; λ_p is the relative slenderness ratio of a U lipped channel profile; b is a coefficient given by Equation (8) and dependent of b_w / b_f ratio.

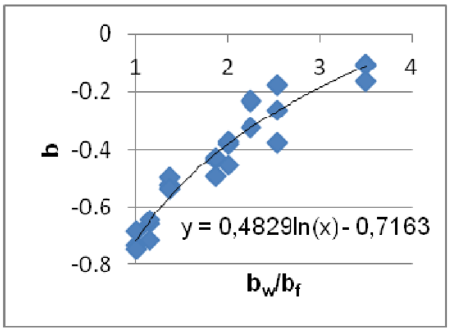


Figure 6: Variation of b coefficient in relation to the b_w / b_f ratio

$$b = 0.4829\ln(bw/bf) - 0.7163 \leq 0 \tag{8}$$

Additionally, due to the possibility that this formulation can be used for other types of cross-section, it was suggested a second formulation for the calculation of the coefficient "b" based on the coefficient for local buckling of cold formed steel profiles, k_l, shown in Figure 7.

$$b = 0.092k_l^3 - 1.0593k_l^2 + 4.0424k_l - 5.8261 \tag{9}$$

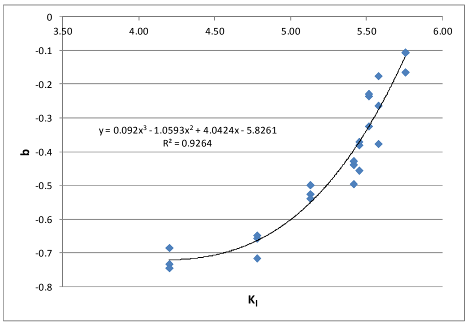


Figure 7: Variation of b coefficient in relation to the k_l coefficient

5. Conclusions

In the present study, it was analyzed analytically and numerically the variation of the yield strength reduction factor for sections subject to local buckling at high temperatures, $k_{\sigma,\theta}$, as a function of the relative slenderness λ_p for U lipped channel profiles. The analytical models used are based on the European Prestandard EN 1993-1-2:2005 and the Brazilian Standard ABNT NBR 14323:2013. The numerical model is based on the Finite Element Method. With the numerical results, it was verified that these numerical results differed from standard analytical results, considering $k_{\sigma,\theta}$ varying only with temperature. Theoretical values of an adjusted reduction factor, named $k'_{\sigma,\theta}$, showed a correlation with the relative slenderness of the cross section, as well as the b_w / b_f ratio.

For λ_p values close to 0.5, it is observed that $k'_{\sigma,\theta}$ becomes very close to $k_{y,\theta}$. It is observed that this slenderness value is below the threshold that defines the profiles subjected to local buckling at ambient temperature, which is around 0.776 . The value 0.5 is still well below even when the limit is 0.776 multiplied by 0.85, as provided by the design rules for fire condition, leading to a limit value of 0.66. For relative slenderness values between 0.5 and 1.0, the theoretical reduction factor is higher than the reduction factor provided by the standards. As for λ_p values greater than 1.0, the $k'_{\sigma,\theta}$ values are generally smaller than those proposed by EN 1993-1-2:2005 and ABNT NBR 14323:2013 and tending to a constant value on average.

Acknowledgments

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