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Local and Distortional Buckling of Cold-Formed Steel Members

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ABSTRACT

Laminar structures have a high post-buckling strength reserve. Cold-formed steel profiles can be taken as a set of thin plate elements. Therefore it is necessary to design this type of profiles taking into account that reserve of strength in post-local buckling modes of failure. The method normally used to design this type of structures is based on the Effective Width concept.

The Effective Widths method, in addition to being highly empirical (giving little contribution to the understanding of the phenomena affecting the stability), leads to the application of a set of relatively complex calculations where the presence of human errors is not always easy to detect. The Direct Strength Method was developed in order to improve the speed and efficiency of the design of cold-formed profiles. This design method uses the buckling loads (for the Local, Distortional and Global modes) gathered from a computer-based analysis and experimentally calibrated resistance curves to predict the strength of the profile.

Using the CUFSM software, a set of tables was created detailing the elastic buckling results (local and distortional) for a wide sample of commercially available profiles. Both Finite Strip Method (FSM) and Constrained Finite Strip Method (cFSM) were used. The objective of these tables was to create a tool to expedite the design of thin-walled profiles using the Direct-Strength Method (DSM).

The automatic application of the MRD in lipped channel profiles was programmed using Matlab. This application was based on CUFSM source code and identifies the local and distortional modes on lipped

channel profiles subject to (i) axial compression and (ii) bending. The constrained Finite Strip Method was used in order to find the global buckling loads. The created software uses these critical loads to calculate the resistance of the profile using AISI's DSM-based specification.
In the last chapter the cold-formed related EC3 provisions are presented (EC3 – Part 1-3) as well as an example of its application on a lipped channel profile subject to axial compression. Finally, the EC3-based software Coldform was used to determine the buckling resistance for a set of profiles. Those results were compared with the ones resulting from a DSM analysis

Key Words: Local and Distortional Modes, Direct Strength Method, DSM, EC3, Cold-Formed Steel Profiles

1. Introduction

The use of cold-formed steel members in the construction industry is motivated by (i) the high structural efficiency of these profiles, namely by having an high strength/weight ratio, (ii) the wide range of shapes (cross-section shapes), (iii) the low-cost of production and transportation.
Figure 1 [Ghersi et al.,(2001)] shows the most common cross-section shapes available for the construction industry:

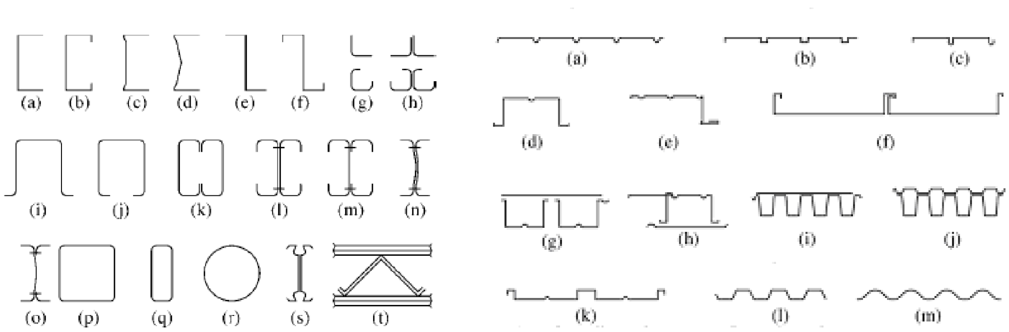


Figure 1 – Most common cold-formed cross-section configurations.

The greater structural efficiency of cold-formed steel members is a great asset of this type of structural solution. However, the reduced thickness of its walls creates problems that engineers must solve. In Prola (2002) there is a list of problems that open cross-section steel members present:

i. Buckling of the thin walls of the cross section in addition to global buckling of the member.
ii. High torsional deformation resulting from the low torsional stiffness of thin-walled open sections.
iii. Warping of sections under torsion.

iv. Consideration of the steel hardening due to folding, resulting on the increase of the yield strength and decrease of ductility.

v. Collapse of the member's wall due to the application of concentrated forces.

vi. Different failure modes both on welded and bolted connections from those observed in hot-rolled steel structures.

Although local instability can occur both on "heavy" and thin-walled profiles, in the second group this instability can occur for relatively low loads. Therefore it is necessary to "explore" the post local-buckling behavior of the member.

Design Codes

Most of the cold-formed steel structure design codes currently in use are based on the Effective Width concept. The Effective Widths method is an approximate process to take into account the effects of local buckling of the member's walls in the resistance of the member. This method consists in reducing the area of each of the members wall, taking into account it's boundary conditions. The member's resistance is then calculated using the reduced cross-section. This indirect way of getting the post-buckling resistance of a member was originally proposed by von Karman in 1932 and subsequently adjusted experimentally by G. Winter (1968).

Direct Strength Method (DSM)

The Direct Strength Method is an alternative method for designing cold-formed steel structures. This method was introduced as an alternative to the effective widths method in the 2004 appendix for the AISI'sIII "North American Specification for the Design of Cold-Formed Steel Structural Members".

The DSM, unlike the other codes, does not resort to the calculation of effective widths nor require iterative methods for calculating the effective properties of the sections. DSM is based on the critical stresses associated with three modes of instability: (i) Local (Plate) Mode, (ii) Distortional mode and (iii) Global modes (flexural or lateral-torsional).

The DSM is an easy to use way to design cold-formed steel structures even for very complex cross-section shapes. It´s only real difficulty is to determine the critical loads (stresses) for local, distortional and global buckling. Although there are some hand-prediction formulas for the critical loads of the most common cross-section shapes, it is easier to use computer programs based on finite element method. CUFSM, developed by Ben Schafer uses the finite strip method to identify and calculate critical loads.

2. Local and Distortional Buckling of commercially-available cold-formed steel members

Figure 2 identifies the cross-section buckling mode deformed configurations for a lipped channel column.

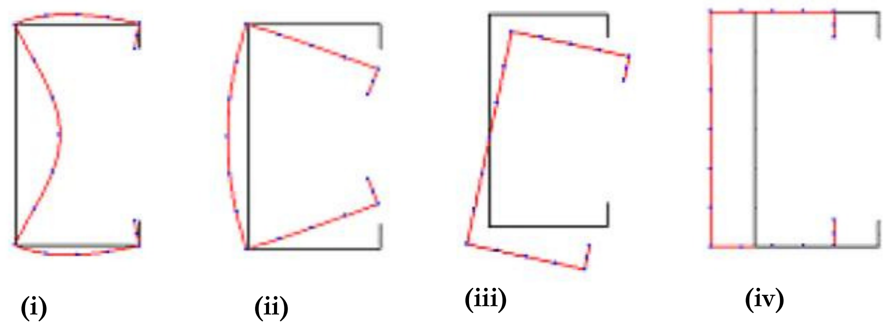


Figure 2 – Cross-section buckling configurations.

For this case the identified buckling modes are:

(i) Local Mode
(ii) Distortional Mode
(iii) Global Flexural-torsional Mode
(iv) Global Flexural Mode

Local Buckling Mode

In this buckling mode, the longitudinal axis of the member remains undeformed. The cross-section deformation, as seen in Figure 2 (i), is due to the bending of the member's inner walls. The outer walls present essentially rigid body displacements. The local buckling of the member depends on the most-likely to buckle of its walls. In simplified terms, local buckling of thin-walled members can be taken as the buckling of a plate whose edges (lines of intersection of adjoining plates of the member) are elastically restrained.

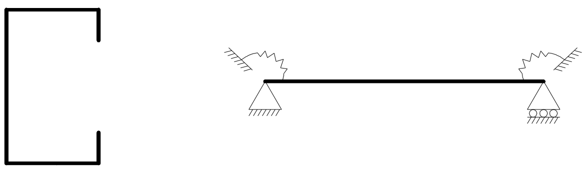
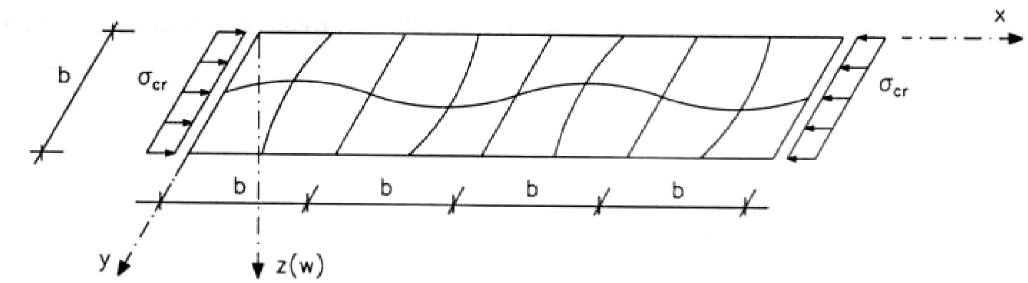


Figure 3 – Local Buckling prediction model.

Figure 3 illustrates the structural model used to predict (using analytical expressions) the local buckling loads. This type of approach, based on plate stability alone, is commonly referred to as “element approach”.

When the length of the plate is more than four times its width, the local buckling mode exhibits half-wavelengths that are close to the plate’s width.



Distortional buckling mode

The study of distortional buckling is still relatively recent. The earliest studies, based on analytical models were the basis to the first design codes that used distortional buckling considerations on the design of thin-walled steel structures.

Distortional buckling is a mode characterized by the rotation of the member’s flange at the flange/web junction, in members with edge stiffeners.

Distortional buckling is associated with the presence of stiffeners. A channel member (cross-section without stiffeners) shows, in general, only one buckling mode: local (plate) mode. The presence of edge stiffeners improves the "performance" of the structural element, but leads to the occurrence of this second mode of instability.

Unlike what happens in the local mode, in the distortional mode there is deformation along the walls junctions (flange/lip), as shown:

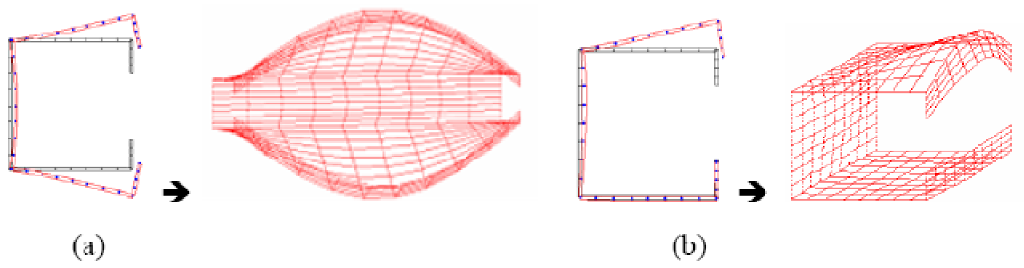


Figure 5 – Distortional buckling mode configurations of na "C" member subject to (a) compression and (b) bending moment.

Buckling Analysis using CUFSM: conventional and constrained finite strip methods

CUFSM applies (i) the conventional Finite Strip Method (FSM) and (ii) the constrained finite strip method (cFSM). The use of the latest method in recent versions of CUFSM aimed to provide a decomposition and modal identification tool. The Buckling modes identified using the conventional FSM are (usually) mixed modes. In some cases, for particularly complex cross-sections, modal identification is difficult or even impossible. The cFSM is used to identify the competing buckling modes that are present.

As an example of modal identification and classification using CUFSM, it was used a channel lipped member, with exterior dimensions 150x70mm (Area = 634.62 mm^2), 2mm thickness and subjected to compression, as shown in the Figure 6:

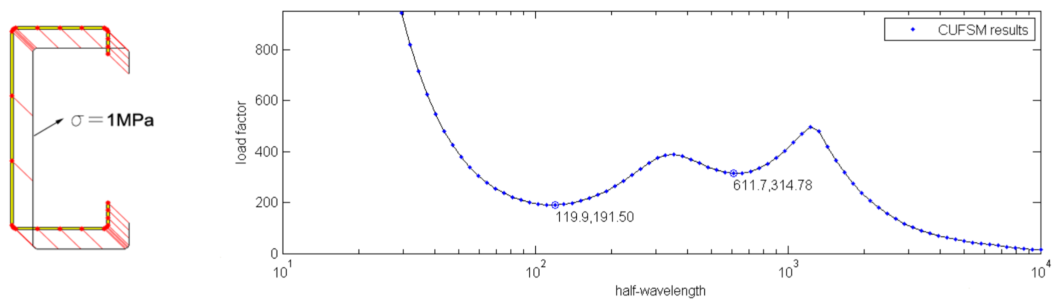


Figure 6 – Modal identification and classification for a "C", using CUFSM.

Taking into account that $f_y = 320MPa$ (S320GD + Z) and reading the information in Figure 6, it is possible to get the members local and distortional buckling loads and half-wavelengths:

Local Mode

Half-wave length: 119.9 mm.

Local buckling stress: $f_{cr\ell} = \text{"}Load\_Factor\text{"} = 191{,}5MPa$

Or, to show the relationship between the buckling stress and the yield stress,

$$f_{crl} = \frac{191{,}50}{f_y = 320} = 0{,}598 \times f_y$$

And the local buckling load is:

$$P_{cr\ell} = 191{,}5 \times A = 191{,}5 \times 634{,}62 = 121{,}53kN$$

Distortional mode

Half-wave length: 611.7 mm.

Distortional mode buckling stress: $f_{crd} = \text{"}Load\_Factor\text{"} = 314{,}78MPa$

Or Or, to show the relationship between the buckling stress and the yield stress,

$$f_{crl} = \frac{191{,}50}{f_y = 320} = 0{,}984 \times f_y$$

The distortional buckling load is:

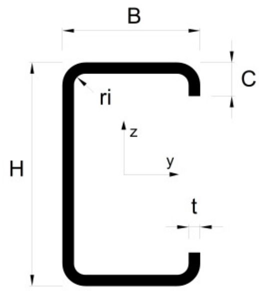
$$P_{cr\ell} = 314{,}78 \times A = 314{,}78 \times 634{,}62 = 199.77kN$$

This CUFSM-based analysis was made for an extensive number of commercially available cold-formed steel members. The analyzed cross-sections were lipped channel, channel and Zed.

The selected suppliers were:

- Perfisa (Portugal)
- Arcelor (All Europe)
- Cemco Steel
- SSMA (Steel Stud Manufacturers Association - USA)
- Acesco (Colombia)
- Skylight (Brazil)
- Sadef (Belgium)

The results were compiled in a series of tables. Figure 7 shows a sample of those tables.



C's

E=210 GPa
v=0,3
G=80,77 Gpa

$M_{cr} = f_{cr} \times W_y$

$P_{cr} = f_{cr} \times A$

H - Cross-section Height
B - Width
C - Stiffeners width
r_i - Internal radius
t - Thickness

$L_{cr\ell}$ - Half-wavelength for local buckling
$f_{cr\ell}$ - Local buckling stress
L_{crd} - Half-wavelength for distortional buckling
f_{crd} - Distortional Buckling Stress

Member		Dimensions (mm)					Area	W_y	Nondimensional Param.				f_y	Finite Strip Analysis Results							
														Compression				Bending			
Produtor	Designação	H	B	C	r_i	t	(mm^2)	(mm^3)	H/t	B/t	C/t	H/B	(Mpa)	$L_{cr\ell}$	$f_{cr\ell}$	L_{crd}	f_{crd}	$L_{cr\ell}$	$f_{cr\ell}$	L_{crd}	f_{crd}
Perfisa	DX51D_110x1.5	110.0	70.0	20.0	1.50	1.50	419.70	15896.66	73.3	46.7	13.3	1.6	140	87.9	192.23	714.4	296.85	64.4	444.92	661.0	454.74
Perfisa	DX51D_110x2.0	110.0	70.0	20.0	1.50	2.00	554.61	20888.34	55.0	35.0	10.0	1.6	140	87.9	344.54	611.7	410.35	64.4	798.54	566.0	624.78
Perfisa	DX51D_110x2.5	110.0	70.0	20.0	1.50	2.50	687.05	25729.65	44.0	28.0	8.0	1.6	140	87.9	542.46	523.7	531.32	64.4	1257.45	484.6	804.57
Perfisa	DX51D_130x1.5	130.0	70.0	20.0	1.50	1.50	449.71	19630.96	86.7	46.7	13.3	1.9	140	102.6	140.53	714.4	261.65	69.6	435.97	661.0	422.03
Perfisa	DX51D_130x2.0	130.0	70.0	20.0	1.50	2.00	594.61	25821.31	65.0	35.0	10.0	1.9	140	102.6	251.57	611.7	362.10	69.6	781.95	566.0	580.87
Perfisa	DX51D_130x2.5	130.0	70.0	20.0	1.50	2.50	737.05	31838.90	52.0	28.0	8.0	1.9	140	102.6	395.59	523.7	470.57	69.6	1230.11	484.6	749.95

Figure 7 – CUFSM results for a sample of C's

3. Direct Strength Method

As mentioned before, the DSM (as implemented by AISI's design code [AISI, 2004], is an alternative procedure to the general method [AISI, 2001] to determine the resistance of cold-formed steel members.
The DSM was first implemented by Hancock et al. (1994) for the consideration of the distortional buckling in thin-walled members subject to compression and bending.
Schafer and Peköz (1999), using the full section, applied the technique for beams considering global, distortional and local buckling.
Schafer (2002) extended the application of DSM to columns, considering local, distortional, flexural-torsional and flexural buckling modes.
The DSM was calibrated using a wide range of experimental results for columns and beams. Nevertheless, the diversity of the sections studied is limited to the most common geometries. The DSM can be applied to any cross-section, although in a more conservative way.

Column design using DSM

The long column strength, P_{ne} follows the same practice as the main specification and uses the AISC (2001) curves to predict the strength of a column. The only difference is that DSM uses strengths (loads) and the main specification curves use stresses. The strength curves for local and distortional buckling of a fully braced column is shown in Figure 8:

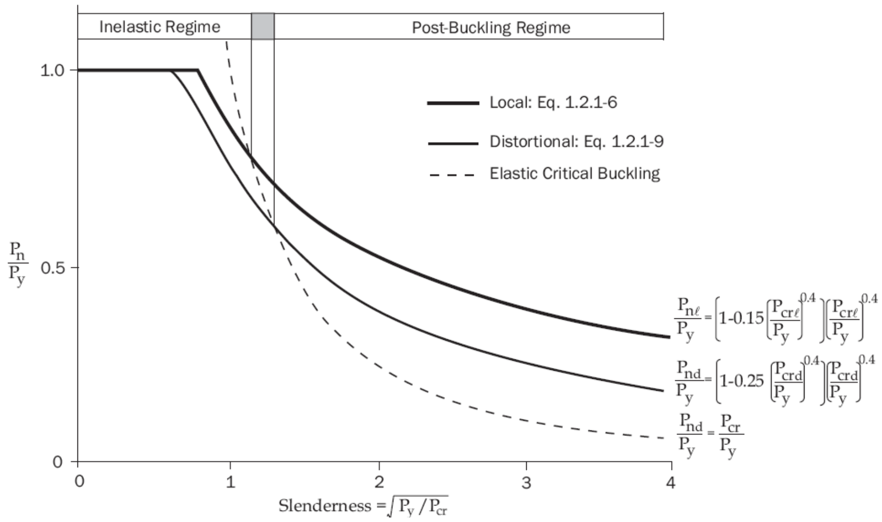


Figure 8 – Local and Distortional Direct Strength Curves for a fully braced column.

The development and calibration of those resistance curves are reported in Schafer (2000, 2002). The resistance of the column is given by the minima of:

(i) Global elastic buckling, P_{ne}.

(ii) Local buckling considering interaction with global buckling mode, $P_{n\ell}$.

(iii) Distortional buckling, P_{nd}.

Beam Design Using DSM

The lateral-torsional buckling strength, M_{ne},follows the same practice as the main specification. Like before, in DSM the resistance cuve must be converted from stresses to a moment. Figure 9 shows the local and distortional strength curves of a fully braced column. The behavior of both curves is similar. The major difference is that the post-buckling strength reserve for the local mode is predicted to be greater than that of the distortional mode.

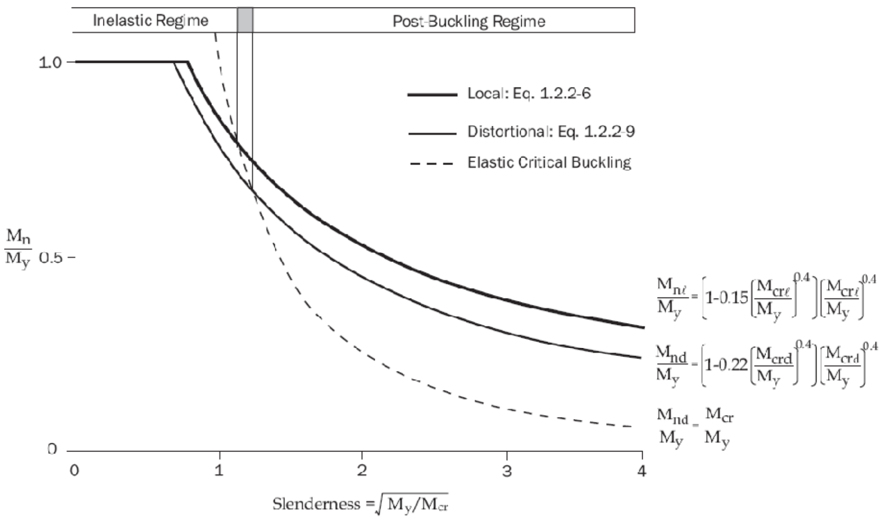


Figure 9 – Local and Distortional Direct Strength Curves for a Braced Beam.

As in the case of the column, the theoretical resistance of the beam is given by a minimum of the three calculated resistances:

(i) Lateral-torsional buckling strength without any reduction, M_{ne}.

(ii) The strength considering local-global interaction, M_{nl},

(iii) The strength considering distortional-global interaction, M_{nd}.

Automatic application of DSM using Matlab

The implementation of Annex 1 of the North American Specification for the Design of Cold-Formed Steel Structural Members is quite simple compared to usual methods of calculation based on the effective width method. Once the buckling loads are obtained by a computational analysis, the member's resistance can be directly calculated by applying the DSM expressions. Using Matlab and the source code for CUFSM, a program was created that:

(i) Analyses the member for both compression and bending

(ii) Identifies the local, distortional and global buckling loads and lengths

(iii) Applies the DSM expressions to compression and bending cases

(iv) Applies the main specification interaction formulas for a combination of compression and bending.

Figures 10 and 11 shows a part of that program (part (ii) above) for a C member:

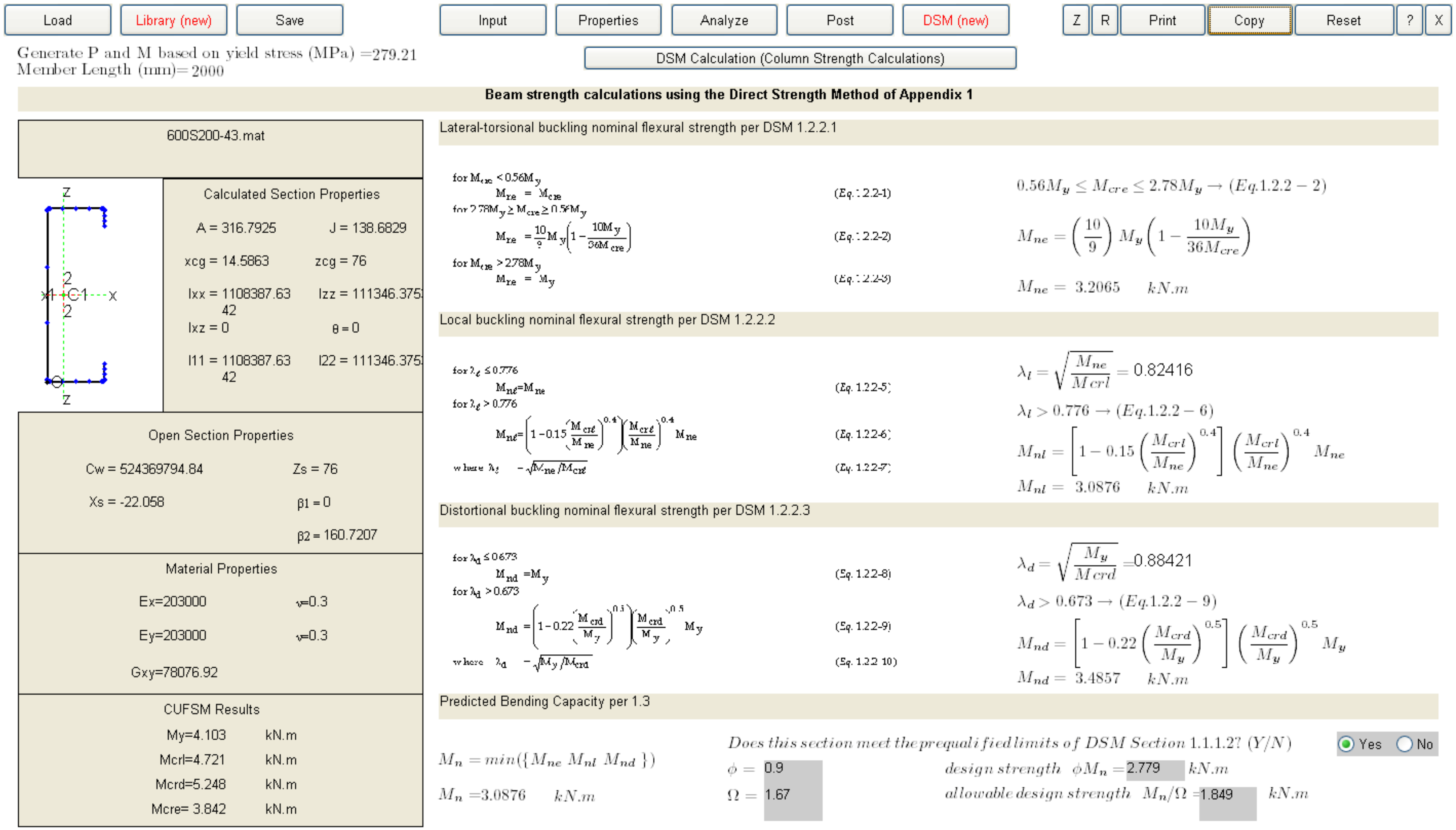


Figure 10 – Beam strength calculation using DSM

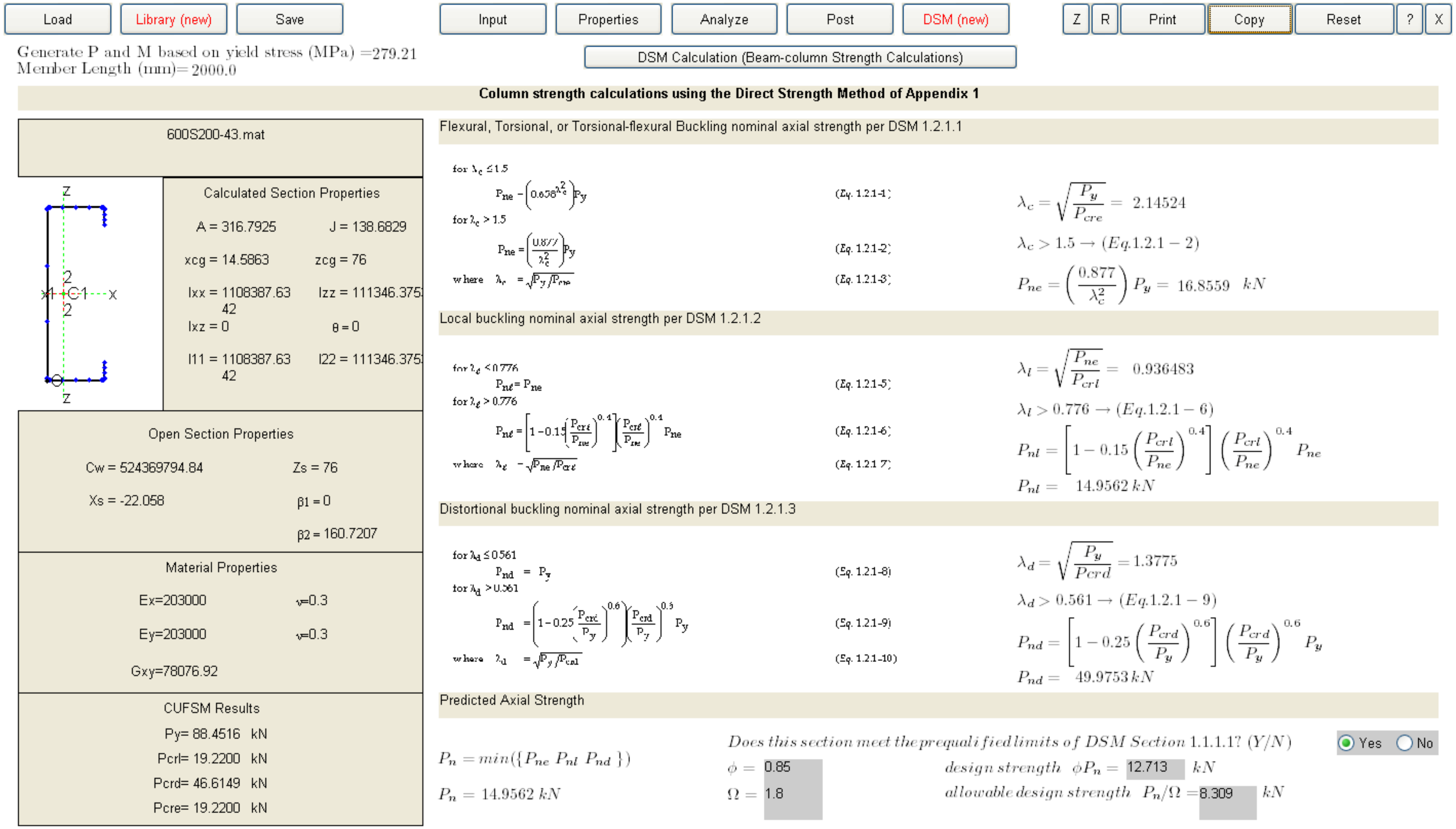


Figure 11- Column strength calculation using DSM

4. Direct Strength Method and Eurocode 3 comparison

The part 1-3 of Eurocode 3 shows the supplementary rules for cold-formed members. Those rules include:

- Effects of the cold forming process in the yield stress of the steel;
- Influence of rounded corners;
- Determination of the section's properties, considering the rounded corners;
- A series of limitations to the cross-section's geometry;
- Methods to determine distortional buckling.

Figure 13 shows a diagram for the safety verification of a member subjected to axial compression using EC3. Other diagrams were created for beam analysis and for members subjected to both compression and bending.

Coldform software was created at University of Napoles by Ghersi et. Al. (2001). It's objective was to provide a tool to compare the Italian, European and North-American design codes. The most recent version of the software uses an old version of EC3 (1996) and has slight differences to the updated version. Nevertheless, Coldform was used to perform a parametric study on a lipped channel member using a cross-section with always the same centerline dimensions, and thicknesses ranging from 0,4 to 4,6 mm. The member's resistance was calculated using the DSM (modified version of CUFSM) and EC3 (using Coldform). The results are shown in the graphics of Figure 12:

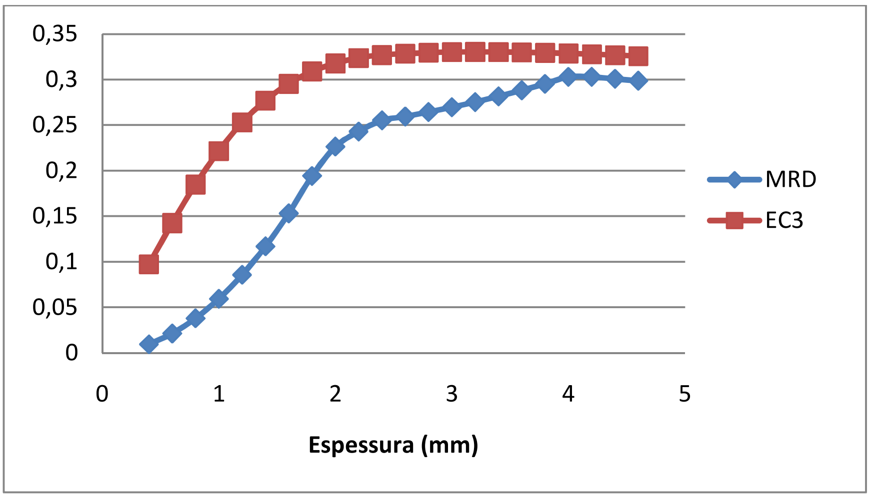


Figure 12 – Comparison between EC3 and DSM for a C member

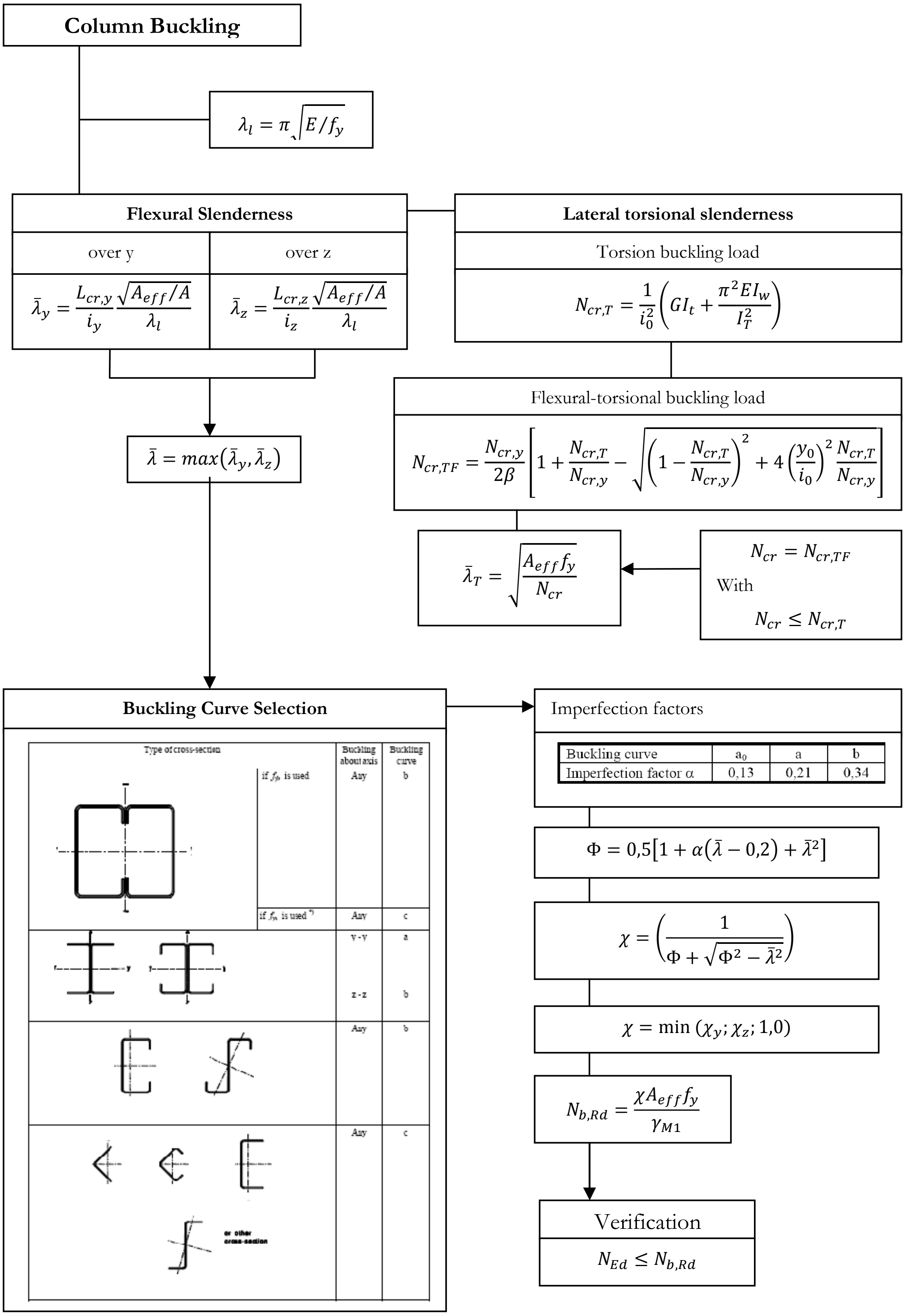


Figure 13 – Diagram for the safety verification of columns by Eurocode 3.

5. Conclusions

The resistance of a thin-walled steel member is in most cases affected by local and distortional buckling. Eurocode 3 uses the effective width method to consider the reduction of resistant capacity of the member in a post-buckling status. The process of getting the reduced (effective) area of the cross-section is sometimes difficult to understand and has little correspondence with the reality of the problem. Therefore, it is easy to make mistakes and hard to detect them. Another limitation of EC3 concerns to the necessity of having a cross-section with a series of limitations to its geometry. Any complex cross-section is difficult to analyse using EC3 and sometimes even impossible. This discourages the possibility of cross-section optimization.

DSM uses a linear stability analysis to identify buckling modes and their buckling loads. Then, its only a matter of using the calibrated resistance curves in order to predict the strength of the profile. The MRD has proven to be a quick method to predict the resistance of cold-formed steel members. CUFSM allows the user to visualize the buckling modes, making it easier to understand the buckling phenomena that affect a given steel member. This helps to avoid errors on the analysis of the section. DSM can be used for almost any open thin-walled cross-section, without an increase of difficulty on the analysis and design.

The use of MRD, as it turned out, is easily programmable making it even faster to use this method. On the other hand, the use of buckling load tables for commercial profiles could contribute to a wider use of the method, with advantages in time savings.

vii. References

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