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FSplines: A Software for Linear Stability Analysis of Thin-Walled Structures, Version 2.0

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Abstract. *FSplines* is a (geometrically) linear stability analysis tool of thin-walled structures with open section (useful for cold-formed steel profiles), that enables obtaining the bifurcation stresses (critical stress, load and moment) and the respective buckling modes by the Finite Strip Method (*FSM*).

The Finite Strip Method: (i) allows analyzing prismatic steel members (commercial structural profiles), (ii) is an alternative to the Finite Element Method (*FEM*), and (iii) has some important advantages over *FEM*. In the present article, two variants of the *FSM* are presented: (i) the Semi-Analytical Finite Strip Method (*SAFSM*), where use is made of trigonometric functions and (ii) the Splines Finite Strip Method (*SFSM*), employing spline functions. The *SAFSM* has the advantage of being less time consuming. Its main restriction is the fact that it only allows modelling simple supported members (pinned restrained). The *SFSM* most important advantage is the ability to model members with all kinds of boundary conditions. This method is, however, more time consuming.

It is worth noting that the bifurcation analysis, performed by the computer application FSplines, is required for the design of cold formed members according to the specifications of international standards.

FSplines 2.0 is the second version of the computer application here presented. In this second improved version more cross-sections are available, and more section properties are presented.

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Keywords: Cold formed structural profiles · Open cross-section thin walled structures · Buckling modes · FSplines 2.0 · Bifurcation stresses · Linear stability analysis · Finite Strip Method

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1 Introduction

FSplines version 2.0 is a software that mainly performs the computation of bifurcation stresses and buckling modes of prismatic thin-walled members by the *SAFSM* and *SFSM* and that incorporates new implementations.

FSplines 2.0 eases the amount of work that designers and civil engineering researchers must do in getting bifurcation tensions and the respective buckling modes of open cross-section thin-walled structural members with different boundary and loading conditions. This version of the software improves the previous one [1] because more types of cross-sections and more section properties are implemented (taking as reference the work of [2]), such as: St. Venant torsion constant, the principal moments of inertia, the distance from centroid to shear center and warping constant.

FSM formulation used by FSplines version 2.0, follows Cheung [3], being a sequel of the work developed by Prola [4] and the version 1 that was developed by Chicaiza [5].

In the second section of this paper, the problems to be solved by *FSplines* 2.0 in the context of linear stability analysis are presented. The third section is devoted to presenting the *FSM* concepts. The fourth section is used to present the *FSplines* version 2.0 basic structure and in the fifth section the software's interface is also presented. In the sixth section, the *FSplines* 2.0 performance is compared with two other informatic applications - *CUFSM* [6] and *NASTRAN In-CAD* [7]. Several numerical examples are used with that purpose. The seventh section is devoted to presenting general conclusions.

2 Elastic Bifurcation Stresses of Thin-Walled Members

The present paper is focused in the computation of bifurcation stresses (critical stresses, loads or moments) and the respective buckling modes (local, distortional and global) [4] for thin-walled members with open cross-sections (generally cold formed profiles), using the Semi-Analytical Finite Strip Method (*SAFSM*) and the Splines Finite Strip Method (*SFSM*).

The critical stress is the lowest bifurcation stress value of all possible instability buckling modes of on structural element (column, bema or beam-column) [8]. Any of the buckling modes generate excessive deformations and consequently leads to the collapse of the structure [9]. In addition, the calculation of elastic bifurcation stresses is a necessary requirement for the modern design of cold-formed structures by the Direct Strength Method (*DSM*) [10]. The different buckling modes (Fig. 1), that can take place in thin-walled and open-section structural members are the following:

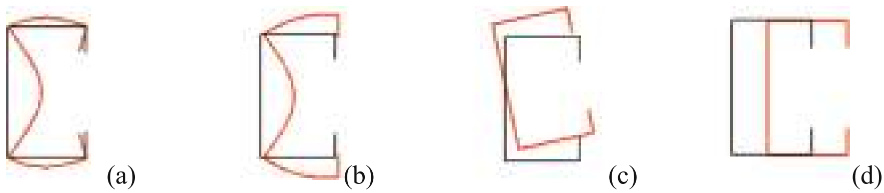


Fig. 1. Buckling modes in a column C subjected to compression: (a) Local, (b) Distortional, (c) Flexo-Torsion (d) Flexural [5].

(i) Local mode (Fig. 1a): the plates suffer deformations, while the lines of bends of the element cross-section remain in the same position. In other words, the cross-sections do not suffer any rigid-body motion [4, 9, 11].

(ii) Distortional mode (Fig. 1b): the cross section experiments a distortional deformation. In this buckling mode some of the cross-section fold lines may undergo a displacement from its original position, unlike what happens in the local mode [4, 12].

(iii) Global mode: it includes the bending (classical Euler's stability problem), flexural-torsional and the lateral-torsional mode. The cross-section moves transversely to the longitudinal direction of the member and/or rotates retaining its original shape [4, 12]. The cross-section suffers a rigid-body translation as shown in Fig. 1d. In the flexotorsional mode (Fig. 1c), the structural members simultaneously experiment a rigidbody translation and a rigid-body rotation. The original cross-sectional shape is however kept [11]. Figure 2 depicts 3D configurations of the different buckling modes for a column under compression.

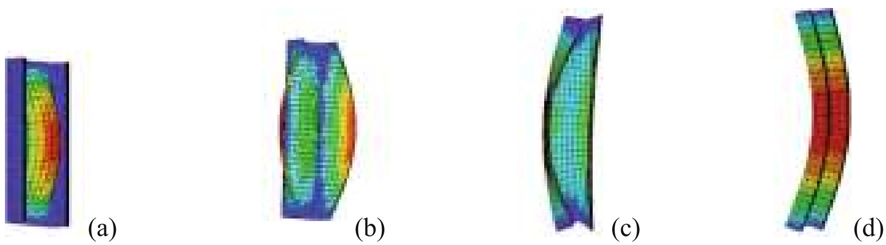
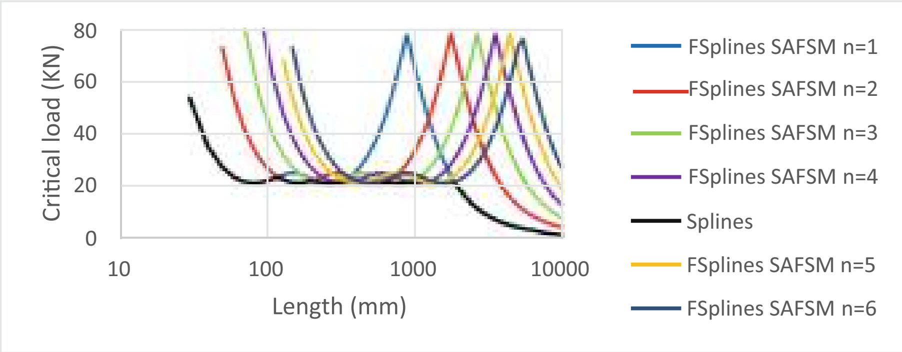
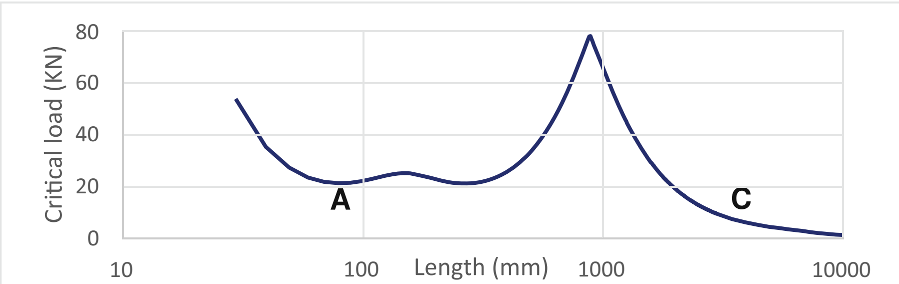


Fig. 2. Buckling modes in a C-type profile subjected to compression: a) Local, b) distortional, c) flexo-torsional, d) flexural.

According to Ádány and Schafer [9], when the *FSM* is used, the buckling modes can be identified more easily in comparison to other methods like *FEM*. This is because in the *FSM* the critical bifurcation stress is a function of the buckling length, i.e. the "signature curve" (i.e., the critical load vs length) depicted in Fig. 3a. Note that, in Fig. 3a, different colors are used to depict curves computed with distinct half-wave lengths (which can be obtained through the *SAFSM*). The black line represents the



(a)



(b)

Fig. 3. Bifurcation loads of: a) the different buckling modes and b) a single half-wavelength VS Length of a C-type profile subjected to uniform compression.

minimum value for all half-wave lengths (which can be obtained through the *SAFSM*, where all the half-wave lengths are grouped; or directly by the *SFSM*).

In this paper, only curves corresponding to single half-wavelength, see Fig. 3b, are presented when *SAFSM* is being used because the others are curves of the same type obtained by its horizontal translations.

One can observe, in Fig. 3b, that the first minimum (point A) of the "signature curve" (for a single half-wavelength) is typically related to the local modes. The second minimum (point B) is typically associated with the distortional type of modes and, at last, the descending branch of the curve, for higher lengths, is associated to global modes.

3 Finite Strip Method

FSM is a useful tool for the analysis of structural problems, being a valid alternative to the *FEM* [13] and presenting important advantages relatively to the *FEM*, particularly for the analysis of prismatic elements.

FSM requires a discretization procedure in which a generic member is divided into several strips, that are parallel to each other. The strips widths are kept constant along the longitudinal axis of the member, and they are connected and constrained to each other. This means that the displacement fields of two contiguous strips are compatible in their interfaces, see [3, 4]. Regarding the kinematic of each strip of the member, it is worth noting that the superposition of the membrane and flexural (out of plane) displacement fields is considered, see [14]. Figure 4 depicts a discretized member according to the *FSM*.

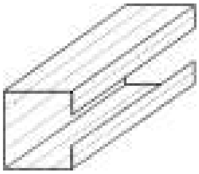


Fig. 4. Discretization of a member according to FSM [4]

3.1 Semi-Analytical Finite Strip Method (*SAFSM*)

SAFSM can be seen as a variant of *FSM* in which trigonometric functions are used for the approximation of the strip's displacement fields. Its main advantage is that the numerical computations required by *SAFSM* are less time-consuming. It's use is however restricted for the analysis of structural elements with a regular geometric configuration (such as thin-walled prismatic profiles) with simple boundary and load conditions [3, 4].

3.2 Splines Finite Strip Method (*SFSM*)

SFSM can be seen as a variant of *FSM* in which splines functions are used for the approximation of the strip's displacement fields, see [15]. It is important to clarify that there are several types of splines functions, which are used according to the calculation requirement. This paper addresses the basic cubic 3 -Spline function, see [16], proposed by Cheung [17] and Fan [18].

The *SFSM* with $_3$-Splines functions maintain the transverse interpolation polynomials and replaces the longitudinal trigonometric functions [16] by a linear combination (summation) of basic cubic functions [10, 16] of equal length of section [15]. An advantage of *SFSM*, in comparison with *SAFSM*, is its ability to give better approximations to the displacement fields in the longitudinal direction [18]. Additionally, the *SFSM* allows considering more complex boundary conditions (for example, fixedfixed, fixed-free, etc.) and a wider range of loading conditions [6].

In *SFSM*, the finite strips have four degrees of freedom along each station (longitudinal division of the finite strip) denoted: "u", "v", "w" y "θ" [9]. For the in-plane behavior (displacements "u" and "v"), a 2D plane stress condition is assumed, while for the out-of-plane behavior (displacement "w" and "θ") [3, 4]. As usual, the displacement functions are obtained from the product of nodal displacements by the shape functions (both in the longitudinal and transversal direction) [10].

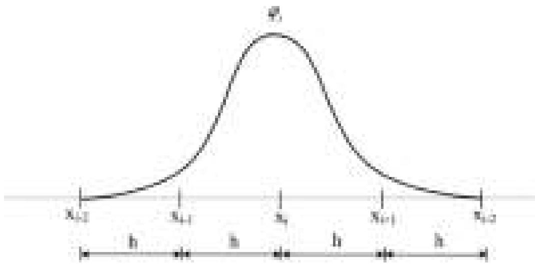


Fig. 5. Development of the basic cubic function B_3S in a generic domain [4]

In the longitudinal direction, the local cubic spline function (B_3S) is divided into four segments (represented by the letter "h") of equal length, but with different combinations of polynomials in each segment. The function mentioned is depicted in Fig. 5 [4, 10]. Equation (1) defines the spline function depicted in Fig. 5.

$$\varphi_i(x) = \begin{cases} 0 & x \le x_i - 2h \\ (x - x_i + 2h)^3 & x_i - 2h \le x \le x_i - h \\ h^3 + 3\left\{h^2(x - x_i + h) + h(x - x_i + h)^2 - (x - x_i + h)^3\right\} & x_i - h \le x \le x_i \\ h^3 + 3\left\{h^2(x_i + h - x) + h(x_i + h - x)^2 - (x_i + h - x)^3\right\} & x_i \le x \le x_i + h \\ (x_i + 2h - x)^3 & x_i + h \le x \le x_i + 2h \\ 0 & x \ge x_i + 2h \end{cases} \tag{1}$$

An arbitrary function f(x), with domain $a \le x \le b$, can be approximated by using 3 functions as the one presented in Eq. (1) and depicted in Fig. 5. The after mentioned domain is subdivided into m parts with lengths h = (a − b)/m. Note that $(m + 3)$ "stations" are defined. The interpolation schemes with 3 functions introduce additional intervals at each end, that are added to the m subintervals, see Fig. 6 and [4].

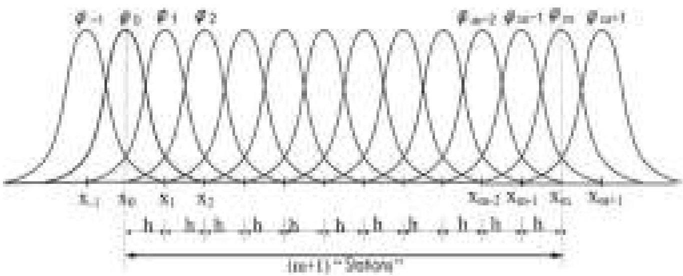


Fig. 6. Series of functions B_3 Splines combined linearly [4].

The arbitrary function f(x) is the approximated by the linear combination (summation) of (m + 3) B_3S functions [4, 10, 15, 19], see Fig. 6, according to Eq. (2),

$$f(x) \approx B_3S(x) = \sum_{i=-1}^{m+1} \alpha_i \varphi_i(x) \quad (2)$$

where α_i are some coefficients to be computed, see [4], and $\varphi_i(x)$ are the local B_3S functions.

4 Structure of FSplines Software

FSplines was programmed with Visual Basic and using the Fortran routines *ALESA* and *ALESPL* provided by Prola [4]. For the numerical computation of eigenvalues and eigenvectors (i) the sub-space method is applied when positive matrices are defined; and (ii) the "Lapack" subroutines are used when tensile and compression stresses take place simultaneously. OpenGL and OpenTK libraries were used for generating *FSplines* graphical outputs. Figure 7 shows the general flow-chart of *ALESA*, *ALESPL* [4] and *FSplines* [5].

Fig. 7. General flow diagram of the *ALESA*, *ALESPL* [4] and *FSplines* [5].

5 Use of *FSplines* 2.0 Interface

This section presents the *FSplines* 2.0 user interface for data input. Some analysis results of two illustrative examples are used with that purpose.

5.1 FSplines Illustrative Examples

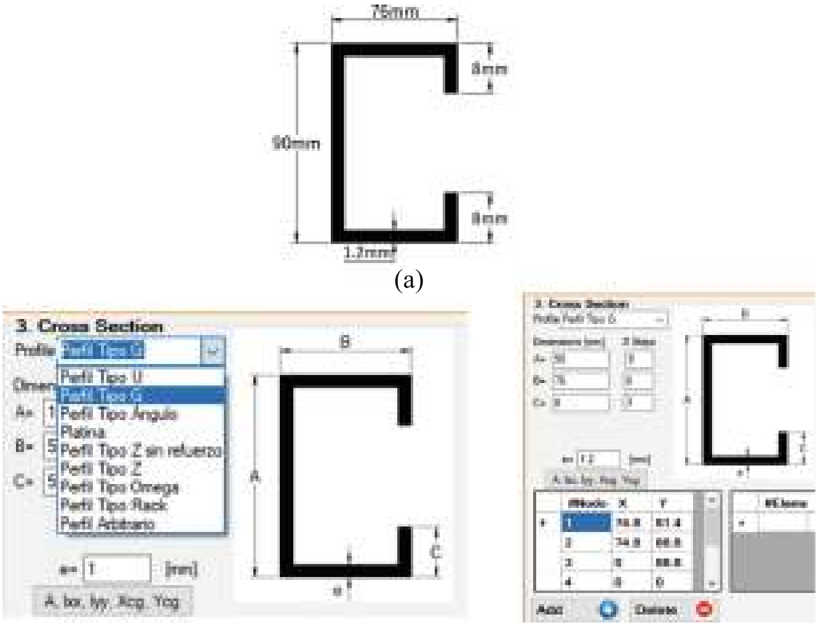
Analysis of a Simply Supported Column with SAFSM
The first example addressed is a simply supported (pinned support) steel C-column, under uniform compression. *SAFSM* was used more examples are detailed in the references [1, 5] and other examples will be incorporate in the *FSplines* 2.0 user's Manual. The following steps illustrate the use of the software's interface:

I. For the idealization of the problem, one has the following steps:
   1. Selection of the type of element to analyze (See Fig. 8a). The first option was selected since, in this case-study, the member is under uniform compression.

(a) (b)

Fig. 8. (a) Selection of the type of the element to analyze (in this case is a column used for the validation of results); (b) Entering the material properties

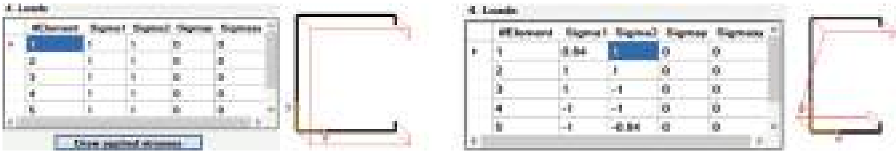
   2. Input of the properties of the material, see Fig. 8b. The software requires the input of the following parameters: elastic modulus in the two directions (E1 and E2) and the corresponding Poisson coefficients v1 and v2. For isotropic structural materials like steel one has E1 = E2 = 210000 (MPa); v1 = v2 = 0.3.



(a) (b) (c)

Fig. 9. (a) Selection of profile type (cross-section) (b) Cross-section with dimensions, (c) Input of the dimensions in (*mm*) *FSplines 2.0*.

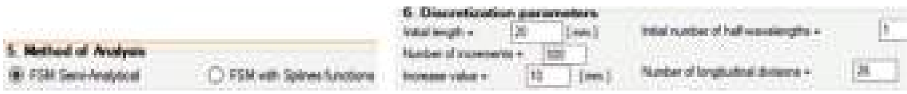
3. Selection of the type of profile (shape of the cross section - See Fig. 9b); input of the dimensions and the definition of the number of strips for each plate, see Fig. 9c. After entering this information, the “Add” button must be activated and the coordinates (with respect to the wall’ mid surface) of the profile are then automatically computed. In this example, see Fig. 10, a C-profile (“Perfil Tipo G”) with dimensions 90 × 76 × 8 × 1.2 mm (external edges, see Fig. 9a) is selected.
4. Stress field definition. For each one of the cross-section’s plates, the software automatically assigns a unit compressive load (per width of the plate) as showed in Fig. 10a. On the other hand, in case of beams, it becomes necessary to generate a flexural stress field as the one presented in Fig. 10b. In the new version is possible to see the applied stresses (red line).



(a) (b)

Fig. 10. (a) Section destined to the entrance of stresses distribution in (a) columns and, (b) beams.

5. Figure 11a illustrates the selection of the analysis method and Fig. 11b presents the software’s menu used for the definition of the discretization parameters. In this menu (i) “Initial length” represents the length (in millimeters) of the member, (ii) “Number of increments” represents the number of length increments for generating the bifurcation stress vs length diagram that usually is use for presenting this type of buckling results., (iii) “Increase value” represents the length (in millimeters) that is being added in each step, (iv) “Initial number of half-wavelengths” represents the number of half-wavelengths defined by the user, (v) “Number of longitudinal divisions” in *SAFSM* it represents the number parts in which the element will be divided and showed in the 3D-view; and in *SFSM*, it’s the parameter of discretization in the longitudinal axis of the structure (This parameter applies for the analysis – only to the *SFSM* - and to display the instability modes). Finally, the “Calculate” button must be pressed to start the calculations.



(a) (b)

Fig. 11. (a) Section destined to the selection of the method of analysis; (b) Space destined to the input of calculation and discretization parameters of the member.

II. For numerical computations, one has.

1. Section properties (See Fig. 12); in the second version more section properties of the cross section are presented.

Fig. 12. Form and properties of the cross section.

2. Bifurcation stress vs length diagram using *SAFSM* with one half-wavelength (see Fig. 13).

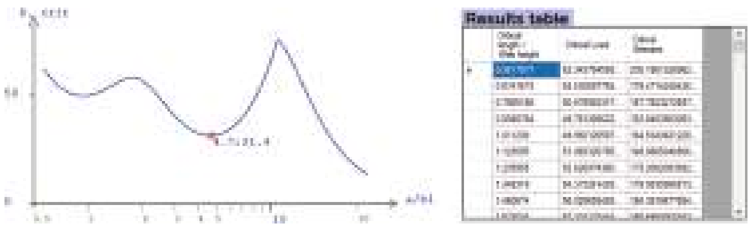


Fig. 13. Bifurcation stress vs length diagram computed with *FSplines 2.0*.

3. Information processed in Excel exported of the *FSplines* 2.0, See Fig. 14. The member length, the critical stress and (i) load (for columns) or (ii) moment (for beams).

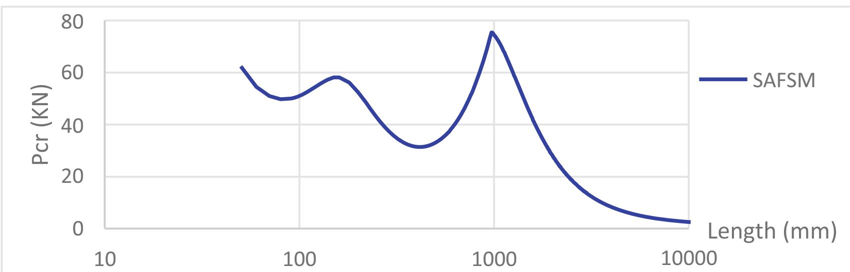


Fig. 14. Bifurcation stress VS length diagram exported to Excel (office-windows)

4. Instability bifurcation mode (See Fig. 15).

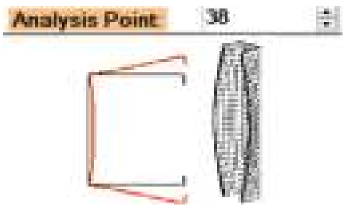


Fig. 15. Deformed in 2D and 3D obtained of *FSplines* 2.0 (analysis for 420 mm column length).

The results obtained by the *SFSM* are shown in Fig. 16 and Fig. 17.

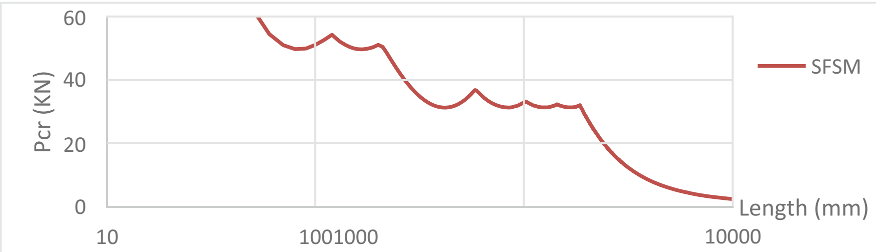


Fig. 16. Curve Bifurcation stresses VS length obtained with SFSM, simply supported column.

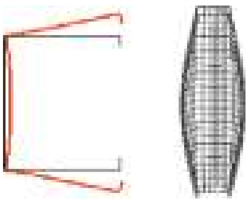


Fig. 17. Deformed in 2D and 3D (analysis for 420 mm column length, where distorcional modo is critical)

Analysis of a "Clamped-Clamped" Column with the *SFSM*

The results for the analysis of a "clamped-clamped" column (i.e., a column with fixed rotations in both edges) obtained with the *SFSM* are illustrated in Figs. 18 (critical load VS length) and 19 (instability mode).

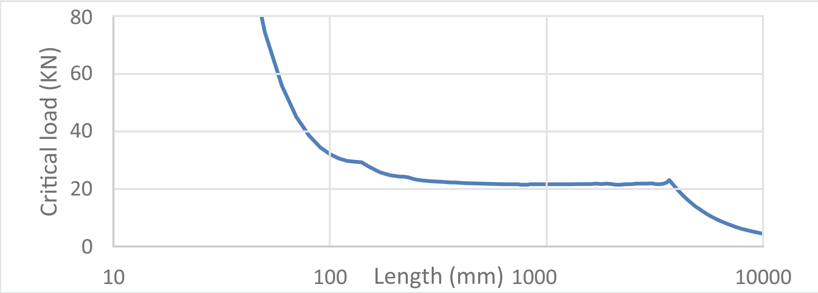


Fig. 18. Curve Critical load VS Length obtained with SFSM; fixed-fixed column.

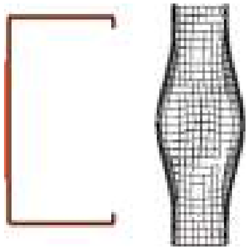


Fig. 19. Deformed in 2D and 3D (length 300 mm).

6 Comparison of the Results

Convergence analysis studies performed by Prola [4], concerning the cross-sectional discretization, proved that the use of models a employing the division of webs into 8 strips; the division of flanges into 6 strips and the division of stiffeners into 3 strips conduct to accurate results.

6.1 *CUFSM* Results

The stability results obtained with *SAFSM* for simply supported C-column with dimensions 101 × 51 × 5.5 × 1 mm (external dimensions) are compared, in Figs. 20 (critical loads) and 21 (critical modes) with simulations obtained with software *CUFSM* [6].

Note that the results obtained with *FSplines* [5] and *CUFSM* [6] match. For instance, in the case of a column with a length of 80 mm, *CUFSM* [6] gives a critical load factor of 101.62, and the stress's value obtained in this point by *FSplines* is the same.

The results of stability analysis obtained by *FSplines* 2.0 with *SFSM* for fixed (clamped) C-column (128 × 78 × 5.5 × 3 mm) are compared, in Figs. 22 and 23, (critical loads and modes) with simulation made by means *CUFSM* [6].

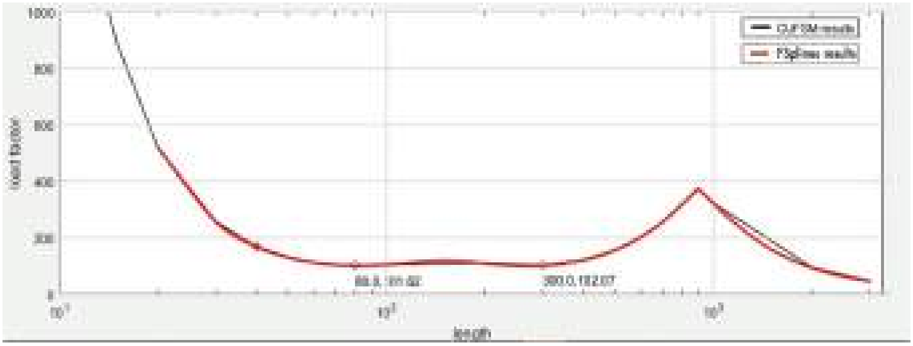


Fig. 20. Comparison between critical local obtained by *CUFSM* [6] e *FSplines* [5] programs.

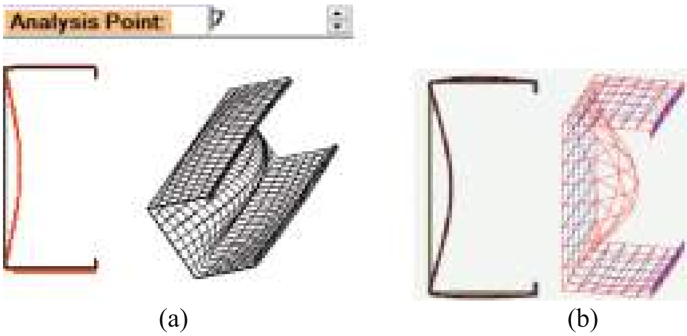


Fig. 21. 2D and 3D instability local mode (length 80 mm) by (a) *FSplines* [5], (b) *CUFSM* [6] programs

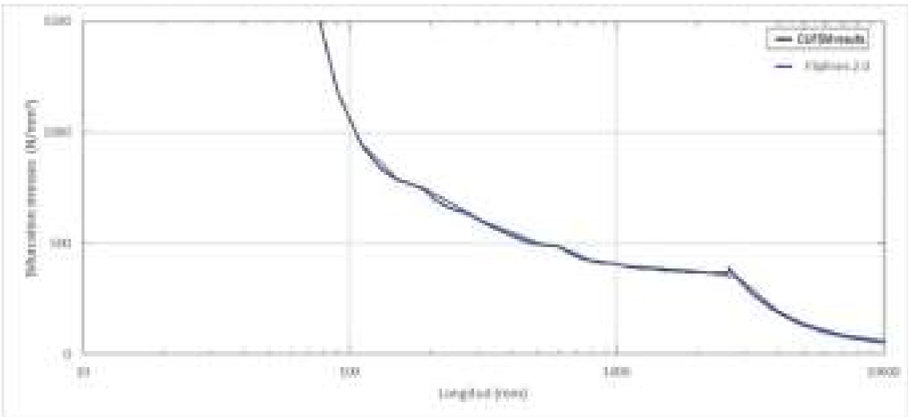


Fig. 22. Comparison between critical loads obtained by *FSplines 2.0* [5] and *CUFSM* [6] (for fixed column)

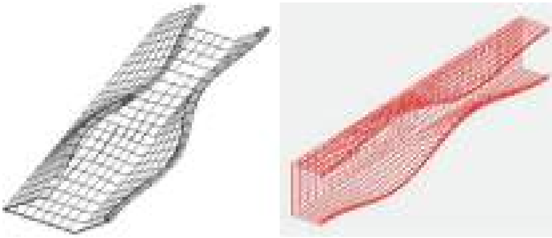


Fig. 23. 2D and 3D instability mode by *FSplines 2.0* [5] and *CUFSM* [6] (length = 790 mm).

6.2 *NASTRAN in-CAD* Results

The stability results given by *SFSM* for a simply supported C-column with dimensions 101 × 51 × 5.5 × 1 mm are compared, in Fig. 24 and 25 (critical loads and modes), with the results given by a Finite Element Analysis performed with *NASTRAN In-CAD* [7].

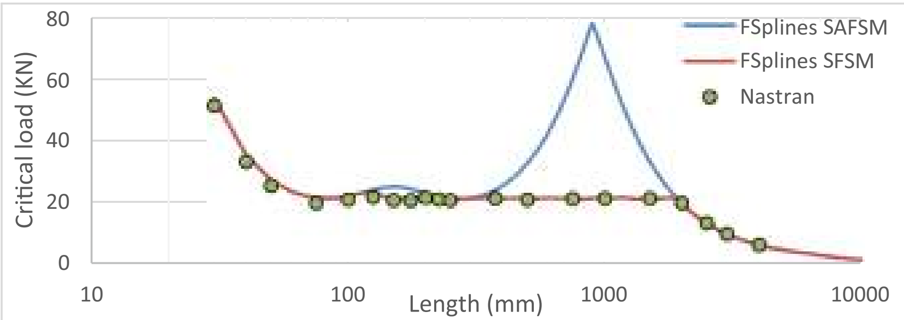
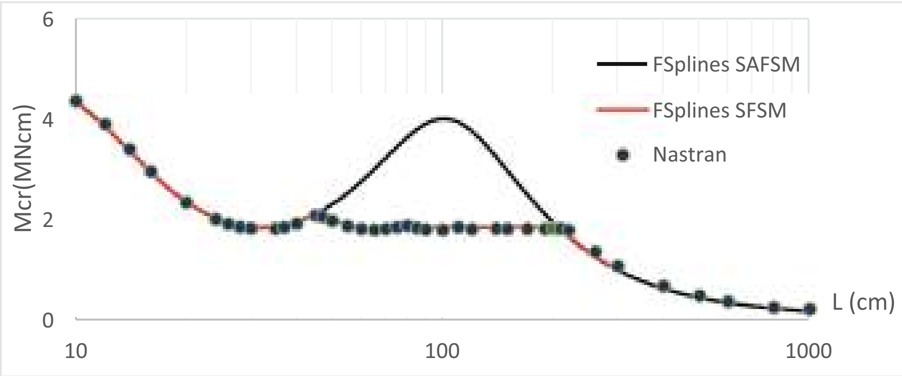


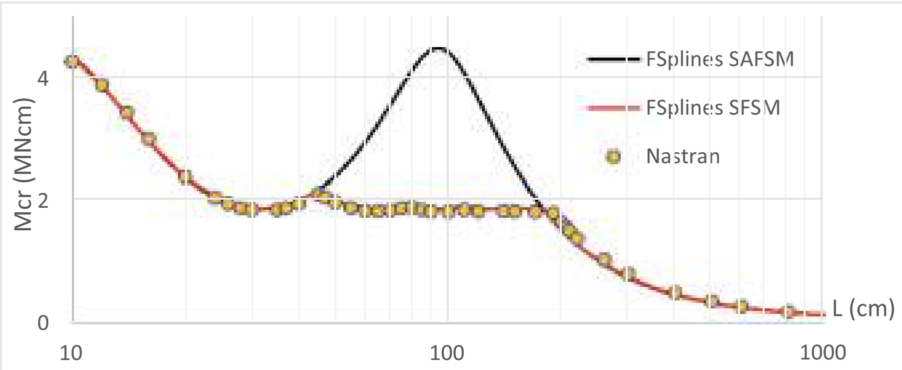
Fig. 24. Comparison between critical loads obtained by *FSplines 2.0* [5] and *NASTRAN In-CAD* [7] softwares.

The stability results given by *SFSM* for simply supported C and Z beams (both with dimensions 128 × 78 × 11.5 × 3 mm) are compared, in Fig. 25, with the results given by a Finite Element Analysis performed with *NASTRAN In-CAD* [7].

Note that, as depicted by Fig. 24 and 25, *FSplines*' results match the ones obtained with *Nastran In-CAD* [7].



(a) C section



(b) Z section

Fig. 25. Comparison between Critical moments obtained by *FSplines* 2.0 [5] and *NASTRAN In-CAD* [7] programs.

7 Conclusions

FSplines 2.0 is a software that allows performing linear stability analysis (critical loads/moments and instability modes) of thin-walled structures (for example cold formed steel beams and columns) subjected to different structural stress fields and with different support conditions by the *FSM*.

FSplines 2.0 is a suitable tool for use of designers and researchers, whose results match the ones given by other numerical tools. The results obtained with the software will allow to apply the *DSM* to design of cold-formed steel structural members (beams and columns).

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FSplines : A Software for Linear Stability Analysis of Thin-Walled Structures , Version 2.0 (Conference Paper)

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Abstract

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FSplines is a (geometrically) linear stability analysis tool of thin-walled structures with open section (useful for cold-formed steel profiles), that enables obtaining the bifurcation stresses (critical stress, load and moment) and the respective buckling modes by the Finite Strip Method (FSM). The Finite Strip Method: (i) allows analyzing prismatic steel members (commercial structural profiles), (ii) is an alternative to the Finite Element Method (FEM), and (iii) has some important advantages over FEM. In the present article, two variants of the FSM are presented: (i) the Semi-Analytical Finite Strip Method (SAFSM), where use is made of trigonometric functions and (ii) the Splines Finite Strip Method (SFSM), employing spline functions. The SAFSM has the advantage of being less time consuming. Its main restriction is the fact that it only allows modelling simple supported members (pinned restrained). The SFSM most important advantage is the ability to model members with all kinds of boundary conditions. This method is, however, more time consuming. It is worth noting that the bifurcation analysis , performed by the computer application FSplines , is required for the design of cold formed members according to the specifications of international standards. FSplines 2.0 is the second version of the computer application here presented. In this second improved version more cross-sections are available, and more section properties are presented. © 2020 All rights reserved. © 2021, The Author(s), under exclusive license to Springer Nature Switzerland AG.

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