A GRAPHIC TOOL TO TEACHING AND VISUALIZATION OF THE STRUCTURAL STEEL BEAM DESIGN: LATERALLY UNSUPPORTED

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Abstract. *The limit state design of steel beam unsupported laterally considers, for critical sections, the bending and shear resistances to be compared with the factored service load actions. Besides, it should be verified the displacements in the serviceability state limit. Base on a didactic experience in the academic life, it was verified that a great number of undergraduate engineering students possesses a considerable difficulty in to visualize and to understand the physical phenomena related with the structural analysis and the steel structural systems behaviour. Considering all these aspects, this investigation presents the obtained pedagogic experience with base in the development of an educational graphic tool for evaluation of steel beams. The educational software was developed in Delphi language, in order to supply a quite pleasant graphic interface for the students allowing a better understanding, step by step, of all stages to be considered in the steel beams evaluation and design. The main objective of the elaboration of this program is to allow to the undergraduate students of the Engineering Course of Faculty of Engineering of the UERJ, FEN/UERJ, a better understanding of the physical phenomena involved in the evaluation of steel structures.*

Keywords*: engineering education, educational tools, steel structures and structural analyses.*

1. Introduction

Based on the significant development of the computer science, the engineers need to adapt to these technologies by reformulating concepts and attitudes. This way, as mentioned by Almeida et al. (1998), the universities, as educational and research institutions, should take this responsibility in order to train these new professionals appropriately, alerting them for the positive and negative aspects of these changes, without forgetting the basic and fundamental characteristics of each profession.

The use of computational programs for analysis and design of structures should be accompanied of an appropriate supervision. Most of these programs work as a closed system (type "*black box*") supplying results depending on as the input data were supplied by the undergraduate engineering student according to the studied problem. Some of the most frequent mistakes happen for incorrect use of units, incorrect definition of the support conditions, among others. By the way, each engineering student should have the capacity to analyse the software results and to decide if they are coherent or not.

Considering all aspects earlier mentioned, this work presents the development of an educational program entitled ANBE - Structural Basic Analysis, developed initially for design and verification of beams in steel structures. The idea of the development of this educational program follows the same strategy of other investigations developed in the Faculty of Engineering of State University of Rio de Janeiro, FEN/UERJ, for several authors, Almeida et al (1997), Vellasco et al (1999), Silva et al (2000), Silva et al (2001) and Silva et al (2002).

2. Structural Steel Beam Design

The most basic structural component is the beam, spanning between two supports, and transmitting loads principally by bending action. Steel beams, which may be drawn from a wide variety of structural types and shapes, can often be designed using little more than the simple theory of bending. However, situations will arise in which the beam's response to its loading will be more complex, with the result that other forms of behaviour must also be considered (Salmon & Johnson, 1990).

For this issue, it is necessary to concentrate on the design of that steel beam class for which strength of materials forms the basis of the design approach. These are denominated restrained compact beams and unrestrained beams. In the first case, the beam must not be susceptible to either local instability or lateral-torsional instability. On the other hand, when unrestrained beams are considered, the structural element is loaded in its stiff plane there exists a tendency for it to fail by buckling in a more flexible plane (by deflecting sideways in the case of the strut).

This investigation is focused in unrestrained beams design and the Fig. 1 illustrates the response of a slender cantilever beam to a vertical end load. This phenomenon is known like lateral-torsional buckling.

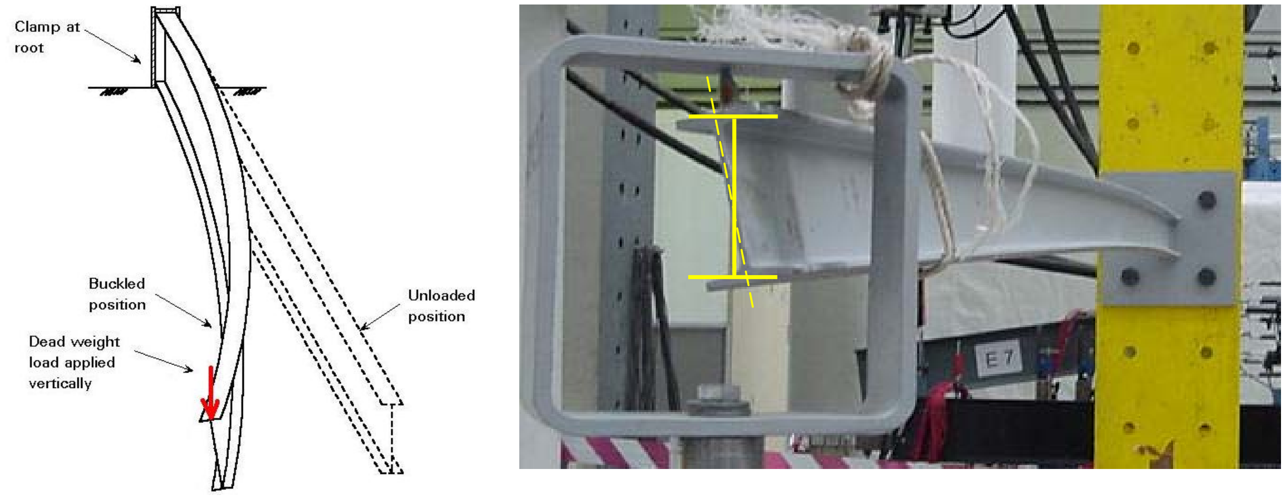


Figure 1. Response of a slender cantilever beam to vertical loading: lateral torsional buckling

There are two categories of lateral support:

a) Lateral support at intervals - Fig. 2(a) to (c) - provided by cross beams, cross frames, ties, or struts, framing in laterally, where the lateral system is itself adequately stiff and braced. The lateral unbraced length (l_b) of the beam is the distance between these two contact points;

b) Continuous lateral support by embedment of the compression flange in a concrete floor slab - Fig. 2(d) and (e).

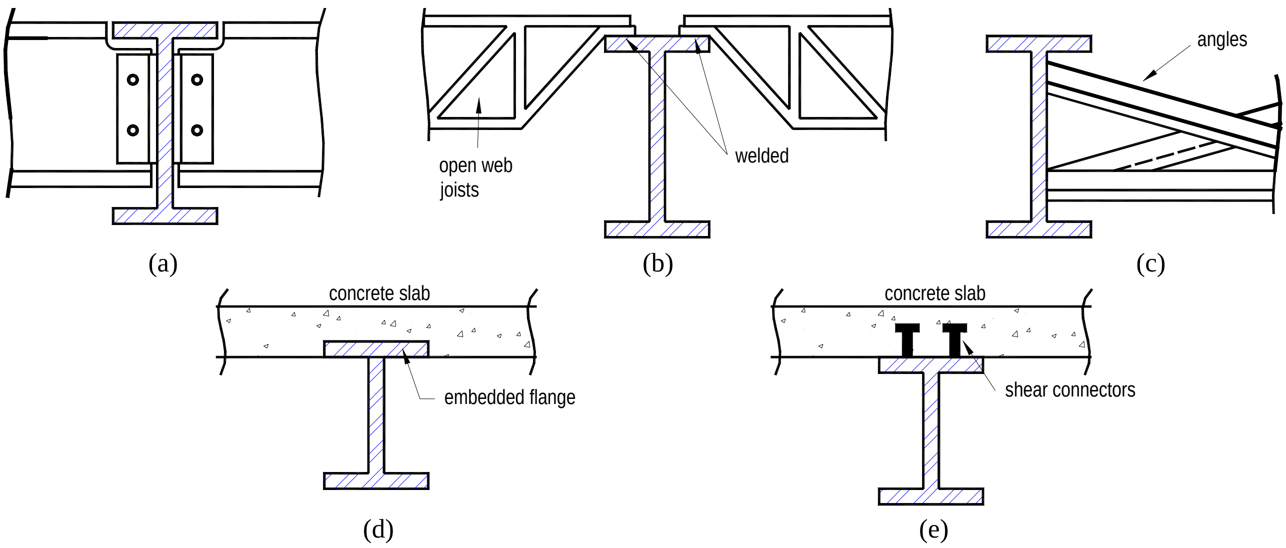


Figure 2. Types of lateral support

Although, it involves both a lateral deflection (u) and twisting about a vertical axis through the web (ϕ) called of warping, as shown in Fig. 2. This type of instability is quite similar to the simpler flexural buckling of an axially loaded strut. Loading the beam in its stiffer plane (the plane of the web) has induced a failure by buckling in a less stiff-direction (by deflecting sideways and twisting).

It is important to mention that the unrestrained beams may be divided in three categories according to the distance between the points with lateral constraint: short beams where the effect of lateral buckling can be disregard, therefore, the beam reaches the moment defined by yielding or local buckling; intermediate beams that present failure by inelastic lateral buckling, which is very influenced by geometric imperfections of the structural element and for the built-in residual stresses during the fabrication process and, finally, long beams that reach the state limit of lateral torsional buckling in elastic range, with the bending moment, M_{cr}.

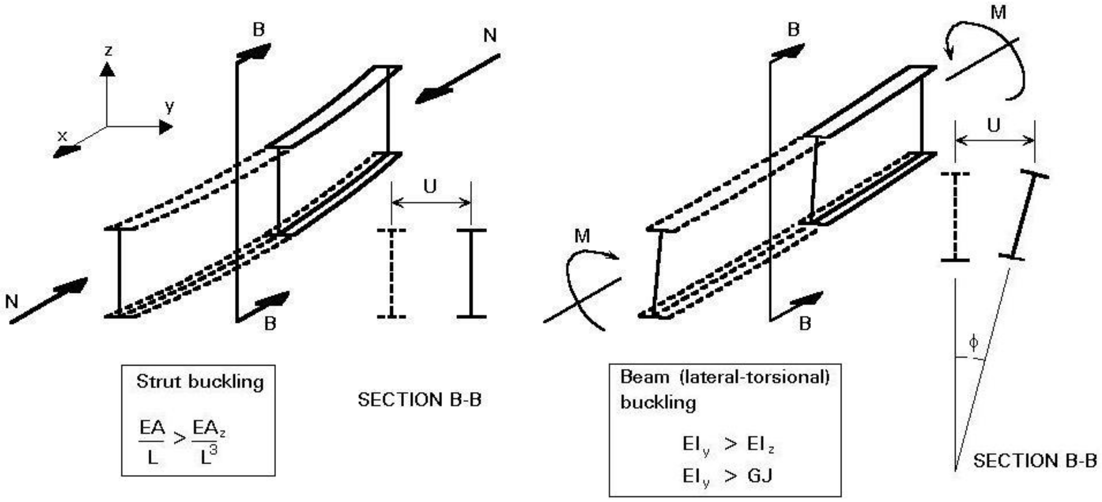


Figure 3. Similarity between strut buckling and beam buckling

2.1. Design procedure for unrestrained beams simply supported subjected to constant moment

The elastic lateral torsional buckling resistance for an I-shaped section under the action of constant (uniform) moment in the plane of the web over the laterally unbraced length L like presented in Fig. (3), considering that displacements and rotations are restrained in the supports ($u = \phi = 0$), may be obtained by the Eq. (1).

$$M_{cr} = \frac{\pi}{L}\sqrt{EI_y GJ + \left(\frac{\pi E}{L}\right)^2 C_w I_y} \tag{1}$$

where L = beam length;
I_y = moment of inertia about y axis;
J = *Saint-Venant* torsion constant;
C_w = warping torsional constant.

Considering “I” or “H” sections, the *Saint Venant* torsion constant J and the warping torsional constant, C_w, may be evaluated by equations presented below. In cases where are considered “I” sections subjected to bending in minor axis and tubular sections, the lateral torsional buckling is not determinant in the beam design due to bending stiffness (EJ) and torsional stiffness of these sections, respectively.

$$J = \frac{1}{3}\left(2b_f t_f^3 + h_o t_o^3\right) \text{ and } C_w = \left(h - t_f\right)^2 \frac{I_y}{4} \tag{2}$$

2.2. Design procedure for unrestrained beams for double symetric sections loaded in the plane of the web

When the moment resistance is based on some of the cross-section fibres reaching a strain ε that is greater than ε_y (that is, $\varepsilon > \sigma_y / E$), buckling is more likely to occur than when strain $\varepsilon < \varepsilon_y$. When elements are inelastic the stiffness as related to the modulus of elasticity decreases; therefore, buckling resistance decreases. The larger the strain requirement the lower must be the slenderness ratios related to the various types of buckling.

According to NBR8800, the required resistance may be obtained from Eq. (3).

$$\phi_b \, M_n \geq M_u \quad with \;\; \phi_b = 0.90 \tag{3}$$

where ϕ_b = reduction factor for flexure;
M_n = nominal bending moment;
M_u = factored service load bending moment;

Figure 4 shows the effect of laterally unbraced length L_b on the lateral torsional buckling resistance. Of course, local buckling may result in lower moment resistance M_n if the plate element (flange or web) width / thickness ratios are too high. By the way, according to the L_b value, different equations should be used. The limits are evaluated by Eqs. (4) and (5).

$$L_p = 1{,}75 \;\; r_y \sqrt{\frac{E}{f_y}} \tag{4}$$

$$L_r = \frac{19{,}9 \;\, r_T^2 \;\, h}{b_f \;\, t_f} \frac{1}{X} \sqrt{1\sqrt{1 + X^2}} \quad \text{with} \;\; X = \frac{40{,}75}{C_b E} \left(f_y - f_r \right) \left(\frac{r_T h}{b_f t_f} \right)^2 \tag{5}$$

where b_f = beam flange width;
f_r = residual stress;
f_y = yielding stress;
h = beam height;
r_T = radius of gyration about weak axis of the section formed by the compressed flange plus 1/3 of the compressed web region;
r_y = radius of gyration about weak axis;
t_f = beam flange thickness;
C_b = coefficient to account for increased moment resistance of a laterally unsupported beam segment when subjected to a moment gradient, Eq. (6)
E = Young´s modulus

$$C_b = 1{,}75 + 1{,}05 \left(\frac{M_1}{M_2} \right) + 0{,}3 \left(\frac{M_1}{M_2} \right) \leq 2{,}3 \tag{6}$$

where M_1 e M_2 = smaller and larger end bending moments in the unbraced segment (see Fig. 4). The ratio M_1/M_2 is negative when the moments cause single curvature, that is, the most severe loading case with constant bending moment gives C_b = 1.0. The value of C_b is also to be taken as 1.0 for cantilevers and for “members where the moment within a significant portion of the unbraced segment is greater than or equal to the larger of the segment end moments.”

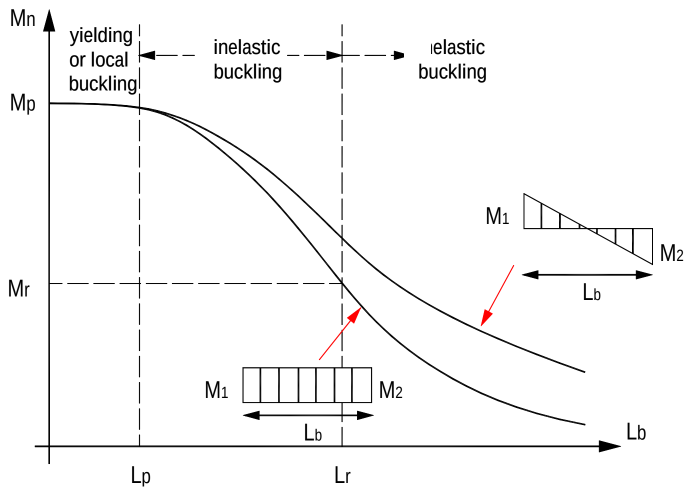


Figure 4. Nominal resistance M_n of “compact” sections as affected by lateral-torsional buckling

Table 1 presents the equations for evaluate the bending moment resistance according to L_b values.

Table 1. Bending moment resistance according to L_b values

Case	M_n
$L_b \le L_p$	$M_n = M_p = Zf_y$ (7)
$L_p < L_b \le L_r$	$M_n = M_p - (M_p - M_r)\dfrac{L_b - L_p}{L_r - L_p}$ (8) where $M_r = W_x(f_y - f_r)$ (9)
$L_b > L_r$	$M_n = M_{cr} = C_b W_x \sqrt{(f_1)^2 + (f_2)^2}$ (10) where $f_1 = \left(\dfrac{0{,}69E}{L_b h / b_f t_f}\right)$ (11), $f_2 = \left(\dfrac{9{,}70E}{(L_b / i_T)^2}\right)$ (12) and $i_T = \sqrt{\dfrac{t_f b_f^3 / 12}{t_f b_f + h_0 t_0 / 6}}$ (13)

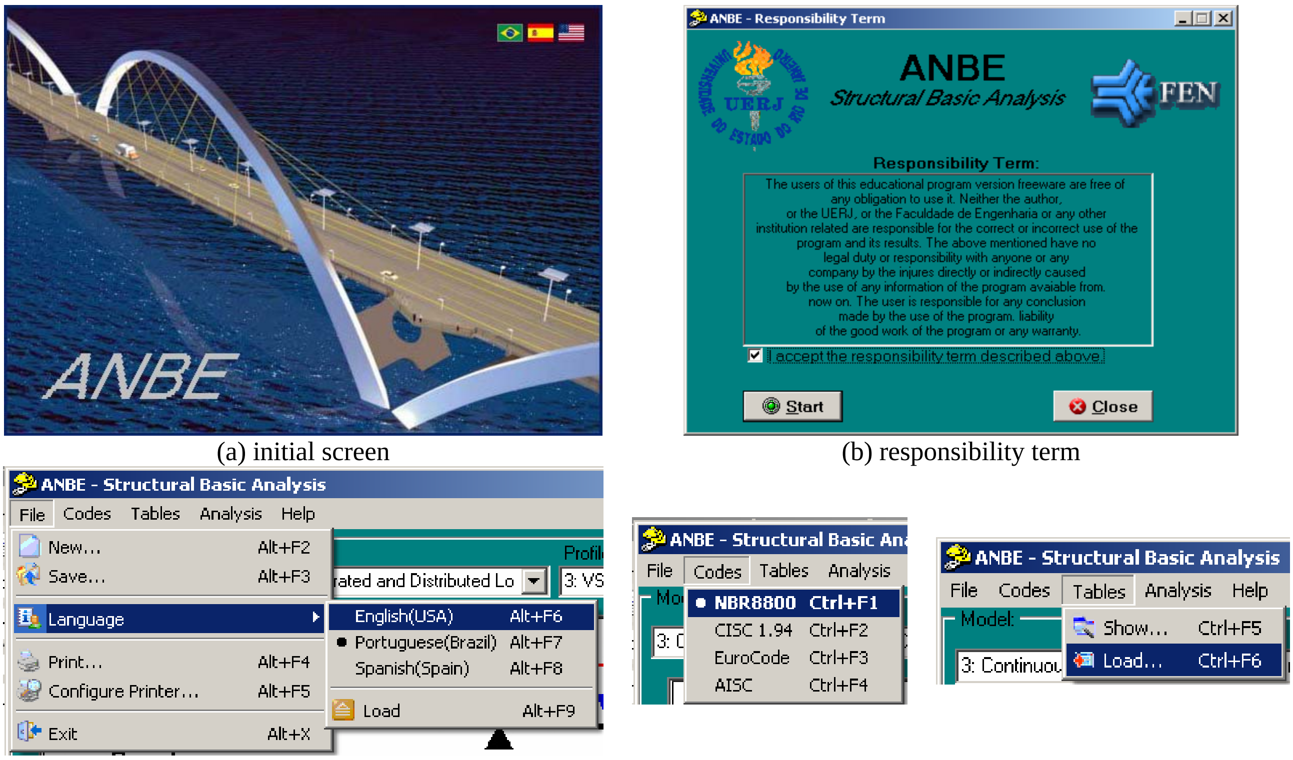
3. Educational Software - ANBE (Structural Basic Analysis)

The development of a graphical educational software in order to motivate the undergraduate engineering students to understand the structure steel beam design led to adoption of the DELPHI programming language (Santos and Reis, 1998). The ANBE (Structural Basic Analysis) software architecture was based on the use of several independent windows screens starting from the windows platform.

The engineering students use these windows screens to input data by filling block spaces or selecting buttons. This software may be used in Windows or Linux platform. It must be emphasized that the ANBE program is currently used as didactic software inside of a public teaching institution and the Linux platform represents an extremely interesting option due to gratuitousness of this operating system licenses.

The actual version of this educational software may be used in three different languages (Portuguese, Spanish and English) such as presented in Fig. 5(a). This command is presented in the menu *File*, *Language*, see Figure 5(c). Figure 5(b) presents the responsibility term that should be accepted by the user to start the software utilization.

As described previously, this educational software is in agreement with the NBR8800 (1986) corresponding to the Brazilian Code to Steel Structures Design and Detailing. However, another three codes are implemented in the software: Canadian (CISC 1.94), European (Eurocode 3) and American (AISC). These options can be accessed on the menu *Codes* like presented in Figure 5(d).



(a) initial screen (b) responsibility term

(c) language settings (d) code specification (e) sections table visualisation

Figure 5. Initial software settings

The developed educational software modulus may be used for six different beam / support configuration: continuous beams with 2, 3 or 4 spans, considering uniform distributed loading (beam self-weight, per example) and concentrated load (secondary beams). After choose the beam type, the engineering student should specify the material, the profile and the geometrical parameters such as distance between supports, unbraced length, concentrated load position and the unbraced length. After this, the user should pick the *Calculate* button and the software results appearance on the *Results* window.

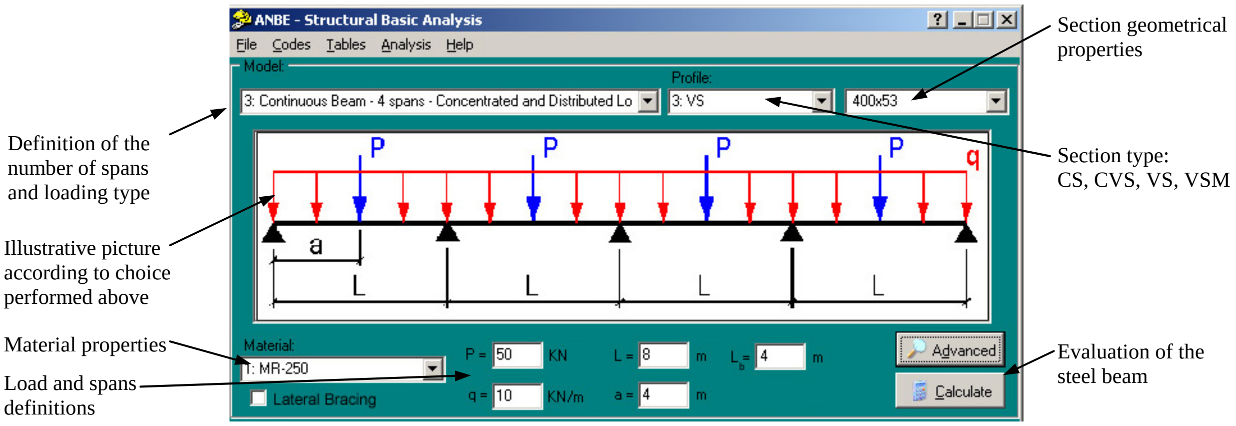
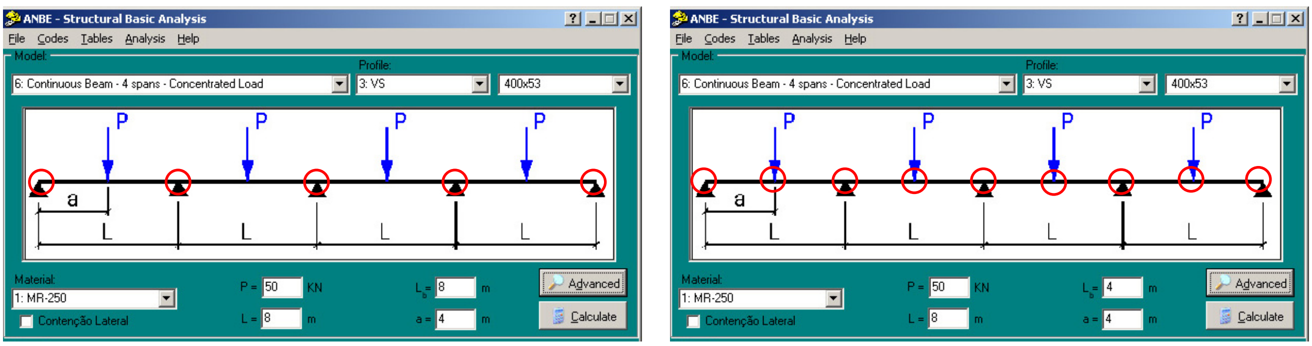


Figure 6. The main screen of the educational software *ANBE*

3.1. Didactic Examples

Two didactic examples are presented in this section. The first situation considered that the lateral bracings are placed only on the supports. In this case, the constant C_b is taken equal to 1.0. For the second example, the unbraced length is considered as half of the distance between the supports, that is, placed in the load application point such as may be observed in the Fig. 7. In both examples, $P = 50\ kN$, $L = 8\ m$ and $a = 4\ m$. The red circles indicated the lateral bracing positions.



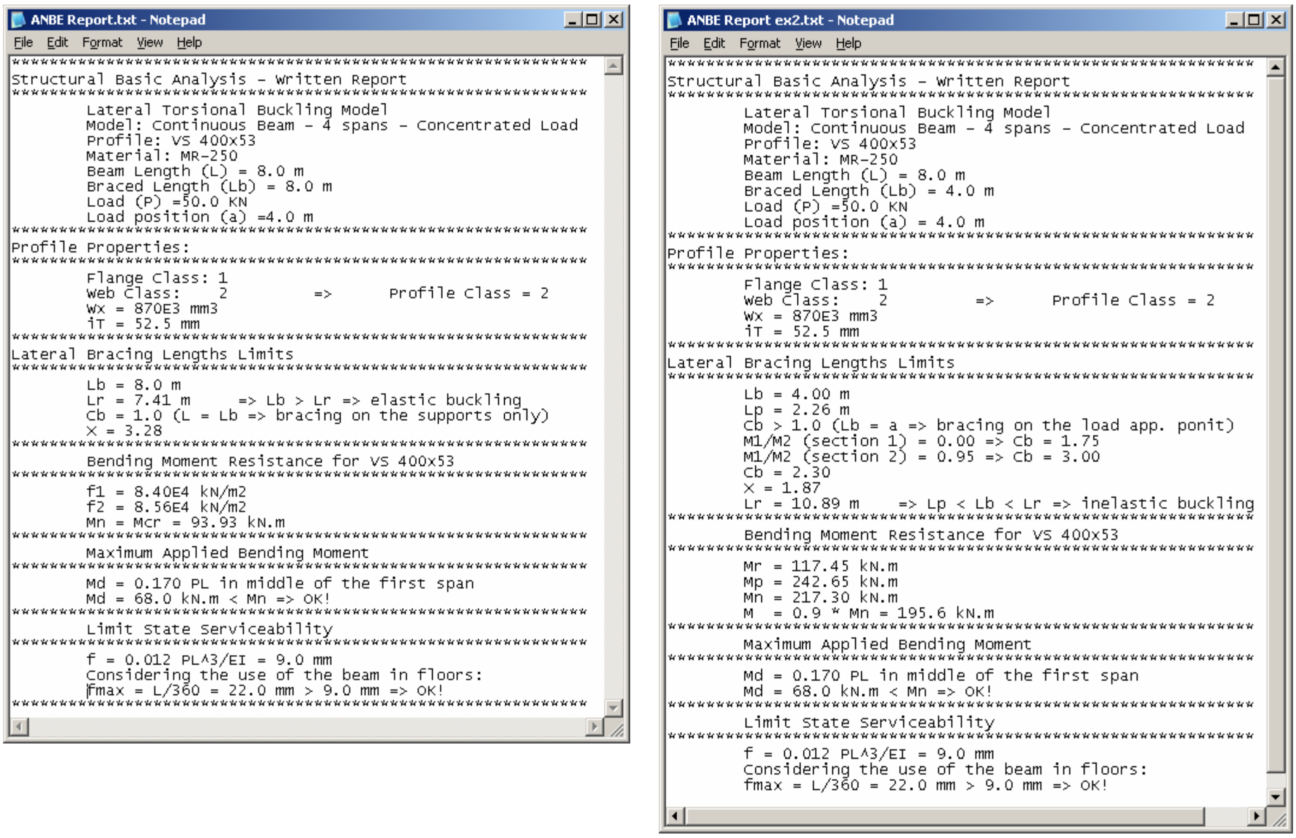
(a) first example (b) second example

Figure 7. Studied cases varying the braced length

After finished the input data step, the *ANBE* results may be obtained through the *Calculate* button and the *Notepad* is automatically opened with the results. For the first example, according to classification presented in Table 1, the larger braced length supply a smaller bending moment resistance equals to 93.93 kN when compared with the 195.60 kN obtained in the second case. The first example considered the case where $L_b > L_r$ and the second, $L_p < L_b < L_r$. These two examples demonstrated the importance of this educational program developed in order to allow to the undergraduate students of the Engineering Course of the FEN/UERJ, a better understanding of the physical phenomena involved in the lateral torsional buckling of steel beams.

4. Relevance of the use of the developed educational program

The present investigation is inserted inside of a context associated to the modernisation of Engineering Courses at Faculty of Engineering, FEN/UERJ. Since 1996, the Faculty of Engineering is engaged in an institutional project called "*The Modernisation of Engineering Courses and Curriculum's at UERJ*". This project, supported and sponsored by CNPq and FINEP, has its main goal related to the modernization of the engineering curriculum and courses, in order to adequate the future engineers to the new engineering professional concepts of the XXI century. This new strategies will prepare them to face and adapt themselves to the constant evolution of technology.



(a) fist example (b) second example

Figure 8. Results supplied by *ANBE* educational program

To fulfil this objective the Faculty of Engineering established a series of goals to create corrective actions to be incorporated in short, medium and long terms (Almeida *et al*, 1998). These investigations confirmed that these goals could only be achieved if a strict methodology of internal quality modernization of the courses/disciplines present in the engineering curricula was to be used (Almeida *et al*, 1998).

This was the main motivation for the creation and implementation of graphical educational programs. The educational software presented in this paper was developed on the Civil Engineering Computational Laboratory, LabCiv, of the Faculty of Engineering of the State University of Rio de Janeiro, FEN/UERJ. The educational program denominated *ANBE* has been used in the undergraduate engineering courses (Strength of Materials, Steel Structures and Special Topics on Structural Problems) as an interactive graphic application for the calculation of the structural steel beams design.

It's clearly noticed that the undergraduate engineering students fills much more motivated to execute the procedures related to structural steel beams design in each stage of the calculation comparing the results supplied by the program with those obtained manually. It has been verified that after an initial stage of learning of the software it is noticed that the students better understand the concepts regarding the structural analysis.

It is also important to emphasize that using the menu Help, Fig. 5, the engineering student can access very important theoretical aspects involved in the steel beam unsupported laterally design. This facility, allied to the fact that steel structures class are supplied at the computation laboratory, it makes possible the fixation of the knowledge in a more efficient way.

The educational software has been applied on the teaching in the undergraduate engineering courses of the FEN/UERJ. Considering this didactic experience, it is verified clearly that the use of graphical tools together with specific courses, mainly those associated to design (Steel Structures and Special Topics on Structural Problems), motivates and stimulates the undergraduate engineering students, as well as facilitates the visualization and understanding of very important theoretical aspects associated to the structural steel beam design.

5. Final considerations

The development of this research project contributed to the implementation and use of a graphical educational tool, the *ANBE* program that evaluates the structural systems response when subjected to several loads. The software described in the present paper was implemented on the Civil Engineering Computational Laboratory, LabCiv, of the State University of Rio de Janeiro, FEN/UERJ.

Based on this didactic experience it can be concluded that the developed graphical educational program helps the undergraduate engineering students to visualize, understand and learn the evaluation process associated with the design of steel beam unsupported laterally with the aid of simple practical examples.

This initiative is currently motivating the development of new user-friendly engineering educational software on the Computational Laboratories of the State University of Rio de Janeiro, FEN/UERJ. These educational computer programs surely contribute to a more efficient engineering learning.

6. Acknowledgements

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