OPTIMUM DESIGN OF BEAMS WITH HOT-ROLLED I-SECTION

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Abstract. *An optimum design offers the ideal solution, seeking the lowest cost with reliability and quality in the results. As such, the combination of optimization techniques together with a process of design makes it a valuable instrument. This research has the objective of presenting optimization problem formulation for steel structures with I shape, based on the Brazilian standard ABNT NBR 8800:2008. An implementation of techniques such as Genetic Algorithm and Sequential Quadratic Programing were developed based on the restrictions on geometry, resistance, maximum displacement and specific usage. This will allow the results to be compared to the results of the CYPECAD 2015 commercial software. The computer program developed was created using the Matlab 2016a GUIDE software, along with an interface that provides the user with easier manipulation. In this paper, it was compared the results between two techniques with the commercial software for 15 beams. The comparison proves the validation of the developed program, and creates a detailed study of the behavior of each technique with reference to the effective resistance of the profiles optimized.*

Keywords*: Optimization, Design, Steel Structures, Computer Program, Graphical User Interface.*

1 INTRODUCTION

The objective of an optimum design is to produce a project with a low cost. Besides the cost-effective project, the ideal solution must attend the requisites for quality and reliability (Alves, 2017). Considering that the weight's element is made up of a homogenous material, the best solution can be reached tending the weight to the lowest possible value that does not compromise the quality and reliability. This solution can be called as the optimum proposal.

The problem approached brings the development of a design program of steel structures. More specifically, this research will be directed to the development of an optimum design of a simply supported beam, with emphasis in optimization techniques and a comparison with a continuous and discrete optimization.

The verification for bending moment of a simply supported beam is going to be discussed, following the criteria of the ABNT NBR 8800:2008. Typically, the profiles that resists better for the bending moment and shear stress, are those which have the highest moment of inertia in the plane of bending. In other words, they are the profiles that have areas farther from the neutral axis. In this way, the ideal shape will be formed by two horizontal plates (superior and inferior) connected by a vertical thinner plate. Therefore, the beams with I-section are the workable solution, because of an easy market access and high resistance due the limitation of buckling (Pfeil, 2015).

Optimization techniques have been explored in the design of steel structures, as can be seen at Novelli et al. (2015), Lubke et al. (2017), Unde et al. (2016), Akbari et al. (2016) and many others. For this research, it will be presented the results for two distinct optimization techniques: Sequential Quadratic Programing (SQP) and Genetic Algorithm (GA). A comparative analysis will be provided between both techniques, in addition with the results of the CYPECAD 2015 commercial software (Fig. 1), using the same structural steel sections catalogue (GERDAU S.A. catalogue).

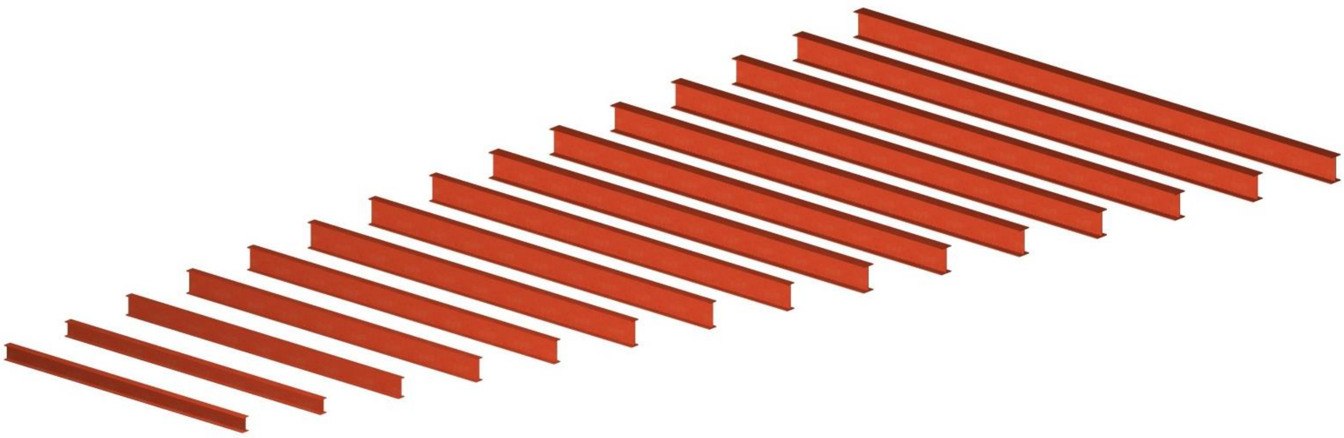

Figure 1. Fifteen simply supported beams with uniform load and hot-rolled I-sections, designed in the CYPECAD 3D 2015 commercial software.

2 GEOMETRIC PROPERTIES

The shape used for the optimum design, it will be I and H profiles, with parallel flanges from the GERDAU S.A. catalogue. Thereby it is important to define the geometric variable used in the optimization problem. Figure 2 shows the basic geometric variables. The variable X is a vector with d, b_f, R, t_w e t_f, and it will be the variable that will be optimized.

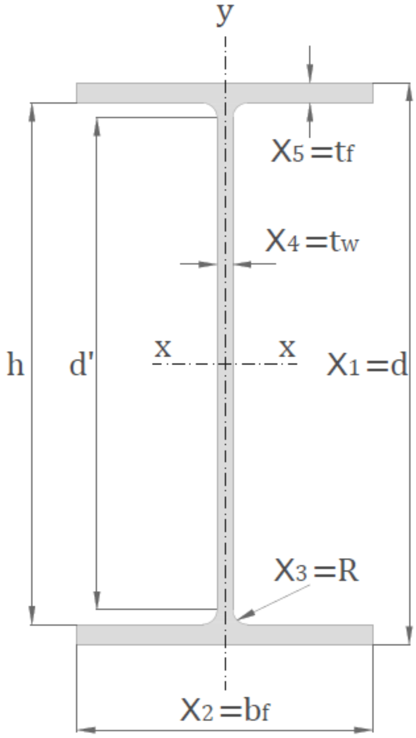

Figure 2. Geometric variables in a hot-rolled I-section, and the vector X.

Where:

X_1: Beam depth (d);

X_2: Flange width (b_f);

X_3: Fillet radius between the web and the flange of a profile (R);

X_4: Web thickness (t_w);

X_5: Flange thickness (t_f);

h: Web depth ($d - 2t_f$);

d': Free web height (without the fillet radius, $h - 2R$).

Just as the basic geometric characteristics, it will be detailed: flange slenderness ratio (1); web slenderness ratio (2); cross-section area (3); moment of inertia about x-axis (4); elastic section modulus about x axis (5); plastic section modulus about x-axis (6); moment of inertia about y-axis (7); radius of gyration around y axis (8); warping constant (9); torsional constant (10).

$$\lambda_f = \frac{b_f}{2t_f} \tag{1}$$

$$\lambda_w = \frac{h}{t_w} \tag{2}$$

$$A_b = 2b_f t_f + ht_w + R^2(4-\pi) \tag{3}$$

$$I_x = \frac{h^3 t_w + b_f(d^3-h^3)}{12} + \frac{R}{6}(h^3 - d'^3) - \pi R^2\left(\frac{R^2}{4} + \frac{d'^2}{4} + d'\frac{4R}{3\pi}\right) \tag{4}$$

$$W_{x_c} = W_{x_t} = \frac{I_x}{d/_2} \tag{5}$$

$$Z_x = \frac{b_f(d^2-h^2)+t_w h^2}{4} + R^2\left[2(d'+R) - \pi\left(\frac{d'}{2} + \frac{4R}{3\pi}\right)\right] \tag{6}$$

$$I_y = \frac{2t_f b_f^3 + d' t_w^3}{12} + \frac{R(2R+t_w)^3}{6} - \frac{\pi R^2}{4}\left[R^2 + (2R+t_w)\left(2R + t_w - \frac{16R}{3\pi}\right)\right] \tag{7}$$

$$r_y = \sqrt{\frac{I_y}{A_b}} \tag{8}$$

$$C_w = \frac{I_y(d-t_f)^2}{4} \tag{9}$$

$$J = \frac{1}{3}(2b_f t_f^3 + ht_w^3) + 2\alpha_1 D_1^4 - 0{,}420t_f^4 \tag{10}$$

Where:

$$\alpha_1 = -0.042 + 0.2204\frac{t_w}{t_f} + 0.1355\frac{R}{t_f} - 0.0865\frac{t_w R}{t_f^2} - 0.0725\frac{t_w^2}{t_f^2} \tag{11}$$

$$D_1 = \frac{(t_f+R)^2 + t_w\left(R + \frac{t_w}{4}\right)}{2R+t_f} \tag{12}$$

3 METHODOLOGY

The design calculation of a steel structure for buildings in Brazil can be found on the ABNT NBR 8800:2008, *Design of Steel and Composite Structures for Buildings* (Brazilian Association of Technical Standards).

Optimization techniques were implemented aiming the optimum design, which gives the lowest cost. In this article, it will be used two distinct techniques: deterministic mathematical model with continuous variable, and probabilistic model with discrete variable. For the mathematical model, it will be used the Sequential Quadratic Programing (SQP), and for the probabilistic model, it will be used the Genetic Algorithm.

The optimum design was implemented in Matlab 2016a, with the Graphical User Interface Development Environment (GUIDE). Consequently, it will be possible to create a Graphical User Interface (GUI) in order to make the studies approachable and more ahead it can be inserted in a structural analysis program.

3.1 Design

The design was made considering a simply supported beam, with a uniform load and hot-rolled I-shapes from GERDAU S.A. catalogue.

For a beam subjected to simple bending, it was computed the design strength and compared to the required strength for the Ultimate Limit State (ULS). The Eq. (13) and Eq. (14) show a normalized verification of the required and design strength. For the Serviceability Limit State (SLS), it was verified the maximum deflection (Eq. (15)).

$$\frac{M_{Sd}}{M_{Rd}} \leq 1 \quad (13)$$

$$\frac{V_{Sd}}{V_{Rd}} \leq 1 \quad (14)$$

$$\frac{f_{max}}{f_{lim}} \leq 1 \quad (15)$$

Where M_{Sd} and V_{Sd} are the required flexural strength and the required shear strength, respectively. Considering a simple supported beam with uniform distributed load (dead and live load combined), M_{Sd} was defined by the maximum value in the Bending Moment Diagram and V_{Sd} by the maximum value in Shear Force Diagram. For each Ultimate Limit State, the design strength for bending moment and shear force can be generalized as M_{Rd} and V_{Rd}. For the SLS, f_{max} is the maximum deflection at midspan and f_{lim} is the deflection limit determined by ABNT NBR 8800:2008.

3.1.1 Design Flexural Strength

The Ultimate Limit States to be verified in beams subjected to flexure are: local buckling, global buckling and plastification of the cross-section. The local buckling is defined as the stability's loss of the flange and/or the web when subjected to compressive stresses, which reduces the flexural strength. The global buckling is the stability's loss of the beam, shown by the appearance of lateral deflections and rotation of its cross-section. The plastification of the cross-section occurs when the bending moment equals to the plastic moment, without showing lateral buckling. Moreover, the plastification will establish a considerable rotation of the section, which results in the development of a plastic hinge. Besides these Ultimate Limit States, it is important highlight that all the design calculation should belong to the elastic structural analysis.

According to the ABNT NBR 8800:2008, Attachment G of non-slender web beams, the design flexural strength for the Ultimate Limit State of web local buckling (WLB) and flange local buckling (FLB) are defined by:

$$M_{Rd} = \frac{M_{pl}}{\gamma_{a1}}, \text{ when } \lambda \leq \lambda_p \quad (16)$$

$$M_{Rd} = \frac{1}{\gamma_{a1}}\left[M_{pl} - (M_{pl} - M_r)\frac{\lambda-\lambda_p}{\lambda_r-\lambda_p}\right], \text{ when } \lambda_p < \lambda \leq \lambda_r \quad (17)$$

$$M_{Rd} = \frac{M_{cr}}{\gamma_{a1}}, \text{ when } \lambda > \lambda_r \text{ (For WLB, Attachment H)} \quad (18)$$

Where:

M_{pl}: Plastic moment;

γ_{a1}: Partial safety coefficient for structural steel (limit state of yielding and buckling);

M_r: Initial yield moment;

λ_p: Slenderness ratio corresponding to the plastification;

λ_r: Slenderness ratio corresponding to the initial yield;

λ: Slenderness ratio corresponding to the cross section element (λ_f for the flange and λ_w for the web);

M_{cr}: Critic moment of elastic buckling.

Flange Local Buckling. The verification of the local buckling for the flange compression will be made using the slenderness ratio of the element. First, it is defined the slenderness ratio $\lambda = \lambda_f$, following by the Eq. (1), and compared to the ratios λ_p and λ_r. Them, it will be possible to certify the limit state that will be governed by the element, simultaneously with the design flexural strength, using the Eq. (16), Eq. (17) and Eq. (18). Below are the equations with the variables for the Eq. (16), Eq. (17) and Eq. (18).

$$M_{pl} = Z_x f_y \tag{19}$$

$$M_r = W_x(f_y - \sigma_r) \tag{20}$$

$$M_{cr} = \frac{0.69E}{\lambda_f^2} W_x \tag{21}$$

$$\lambda_p = 0.38\sqrt{\frac{E}{f_y}} \tag{22}$$

$$\lambda_r = 0,83\sqrt{\frac{E}{(f_y - \sigma_r)}} \tag{23}$$

Where:

f_y: Steel yield stress;

W_x: Elastic section modulus for the extreme compressive fiber, about x axis;

σ_r: Residual Stress of web compression, equal to 30% of steel yield stressf_y;

E: Elastic modulus of steel (200 GPa).

Web Local Buckling. The verification of the local buckling in the web will be made using the slenderness ratio of the element. In the same way, the slenderness ratio $\lambda = \lambda_w$ (Eq. (2)) will be compared to the ratios λ_p and λ_r. Then, it will be possible to certify the limit state that will be governed by the element, simultaneously with the design flexural strength, using the Eq. (16), Eq. (17) and Eq. (18).

However, the slender web verification (Eq. (18)) is different, and it can be found on the attachment H of the ABNT NBR 8800:2008. For hot-rolled I-sections and H-sections beams in the GERDAU S.A. catalogue, the web is compact or non-compact; therefore, this verification is not necessary.

Below are the equations with the variables for the Eq. (16), Eq. (17) and Eq. (18).

$$M_r = W_x f_y \tag{24}$$

$$\lambda_p = 3.76\sqrt{\frac{E}{f_y}} \tag{25}$$

$$\lambda_r = 5.70\sqrt{\frac{E}{f_y}} \tag{26}$$

Lateral-Torsional Buckling. According to the ABNT NBR 8800:2008, Attachment G, the design flexure strength for the ultimate limit state of lateral torsional buckling (LTB) is defined by the inequations (for the M_{pl} it was used the Eq. (19)):

$$M_{Rd} = \frac{M_{pl}}{\gamma_{a1}}\text{, when } \lambda \leq \lambda_p \tag{27}$$

$$M_{Rd} = \frac{C_b}{\gamma_{a1}}\left[M_{pl} - (M_{pl} - M_r)\frac{\lambda - \lambda_p}{\lambda_r - \lambda_p}\right] \leq \frac{M_{pl}}{\gamma_{a1}}\text{, when } \lambda_p < \lambda \leq \lambda_r \tag{28}$$

$$M_{Rd} = \frac{M_{cr}}{\gamma_{a1}} \leq \frac{M_{pl}}{\gamma_{a1}}\text{, when } \lambda > \lambda_r \tag{29}$$

Where:

λ: Slenderness ratio of the beam, defined as $\frac{L_b}{r_y}$, where L_b is the length between points that are either braced against lateral displacement or braced against twist of the cross-section, and r_y is the radius of gyration about y-axis (Eq. (8));

M_{pl}: Plastic moment, defined by Eq. (19);

M_r: Initial yield moment, with the residual stresses, defined by Eq. (20);

M_{cr}: Critic moment of elastic buckling,

$$M_{cr} = \frac{C_b \pi^2 E I_y}{L_b^2}\sqrt{\frac{C_w}{I_y}\left(1 + 0.039\frac{J L_b^2}{C_w}\right)} \tag{30}$$

C_b: The lateral torsional buckling modification factor, for nonuniform moment diagrams, defined by:

$$C_b = \frac{12.5 M_{máx}}{2.5 M_{máx} + 3M_A + 4M_B + 3M_C} \leq 3.0 \tag{31}$$

Where:

$M_{máx}$: Absolute value of maximum moment in the unbraced segment;

M_A: Absolute value of moment at quarter point of the unbraced segment;

M_B: Absolute value of moment at centerline of the unbraced segment;

M_C: Absolute value of moment at three-quarter point of the unbraced segment;

λ_p: Slenderness ratio corresponding to the plastification, given by:

$$\lambda_p = 1.76\sqrt{\frac{E}{f_y}} \tag{32}$$

λ_r: Slenderness ratio corresponding to the initial yield, defined by:

$$\lambda_r = \frac{1.38\sqrt{I_y J}}{r_y\, J\, \beta_1}\sqrt{1+\sqrt{1+\frac{27C_w\beta_1^2}{I_y}}} \quad (33)$$

$$\beta_1 = \frac{(f_y - \sigma_r)W_x}{EJ} \quad (34)$$

Where:

f_y: Steel yield stress;

W_x: Elastic section modulus for the extreme compressive fiber, about x axis;

σ_r: Residual Stress of web compression, equal to 30% of steel yield stress f_y;

E: Elastic modulus of steel (200 GPa).

Validation of Elastic Structural Analysis. The design will be made in the elastic behavior. In this case, the design flexural strength is limited to the following equation:

$$M_{d,res} = \frac{1.5W_x f_y}{\gamma_{a1}} \quad (35)$$

Where:

f_y: Steel yield stress;

W_x: Elastic section modulus for the extreme compressive fiber, about x axis;

γ_{a1}: Partial safety coefficient for structural steel (limit state of yielding and buckling);

3.1.2 Design Shear Strength

The shear resistance is limited to the web yielding and the web buckling, caused by the shear stresses. Therefore, the element that will resist the shear forces will be web. For flexure about the perpendicular axis to the web plane, the design shear strength is given by:

$$V_{Rd} = \frac{V_{pl}}{\gamma_{a1}}\text{, para } \lambda \leq \lambda_p \quad (36)$$

$$V_{Rd} = \frac{\lambda_P}{\lambda_w}\frac{V_{pl}}{\gamma_{a1}}\text{, para } \lambda_p < \lambda \leq \lambda_r \quad (37)$$

$$V_{Rd} = 1.24\left(\frac{\lambda_p}{\lambda_w}\right)^2\frac{V_{pl}}{\gamma_{a1}}\text{, para } \lambda > \lambda_r \quad (38)$$

Where:

$$\lambda_p = 1.10\sqrt{\frac{k_v E}{f_y}} \quad (39)$$

$$\lambda_r = 1.37\sqrt{\frac{k_v E}{f_y}} \quad (40)$$

$$V_{pl} = 0.60A_w f_y \quad (41)$$

$$A_w = dt_w \quad (42)$$

Where:

k_v: The web shear buckling coefficient;

$k_v = 5.0$ when $a/h > 3$ or $a/h > \left(\frac{260}{h/t_w}\right)^2$ and $k_v = 5 + \frac{5}{(a/h)^2}$ for all the other cases;

a: Clear distance between transverse stiffeners, which will be defined as the length between points where the beam is braced (transverse stiffeners just in the supports of the beam).

The type of hot-rolled profiles used for this research, does not need transverse stiffeners. The GERDAU S.A. catalogue I-section and H-sections, has compact and non-compact webs. In this case, the web buckling strength will be sufficient to support the shear stresses (Pfeil, 2015). So, it was decided to raise the web thickness in case that it needs transverse stiffeners.

3.1.3 Deflection Limit

The Serviceability Limit State, is verified by comparing the f_{lim} with f_{max}, Eq. (15). Where f_{lim} is the deflection limit, defined by $L/350$ (according to the ABNT NBR 8800:2008), and f_{max} is maximum deflection due the elastic behavior of the beam, subject to a uniformly distributed load, given by:

$$f_{max} = \frac{5\, Q_{ser}\, L^4}{384\, E\, I_x} \tag{43}$$

Where:

Q_{ser}: Uniform Load, due the Serviceability Limit State combination;

L: Beam's length;

E: Elastic modulus of steel (200 GPa);

I_x: Moment of inertia about x-axis, Eq. (4).

3.2 Deterministic Optimum Design

The continuous optimization will be formulated using the Sequential Quadratic Programing (SQP). For the problem it was used the Optimization Toolbox™ from Matlab. The optimization gives the minimum of an objective function, such that the constraints shall be met. The formulation for the problem is described below, where: objective function – Eq. (44); initial point – Eq. (45); lower and upper bounds – Eq. (46); function of nonlinear constraints – Eq. (47).

$$f_{objective}(X) = 2X_2X_5 + (X_1 - 2X_5)X_4 + X_3^2(4 - \pi) \tag{44}$$

$$X_0 = [\,383 \quad 213 \quad 13 \quad 11 \quad 14\,]\ mm \tag{45}$$

$$[\,148 \quad 100 \quad 10 \quad 4.3 \quad 4.9\,] \leq X \leq [\,617 \quad 325 \quad 16 \quad 17.4 \quad 22.2\,]\, mm \tag{46}$$

$$f_{constraints}(X) = \begin{cases} \{1\} & \dfrac{M_{Sd}}{M_{Rd,FLB}} \leq 1 \\ \{2\} & \dfrac{M_{Sd}}{M_{Rd,WLB}} \leq 1 \\ \{3\} & \dfrac{M_{Sd}}{M_{Rd,LTB}} \leq 1 \\ \{4\} & \dfrac{M_{Sd}}{M_{d,res}} \leq 1 \\ \{5\} & \dfrac{V_{Sd}}{V_{Rd}} \leq 1 \\ \{6\} & \dfrac{f_{max}}{f_{lim}} \leq 1 \\ \{7\} & \lambda_w \leq \lambda_r, for\ WLB \\ \{8\} & \dfrac{a}{h} > 3\ or \quad \dfrac{a}{h} > \left(\dfrac{260}{h/t_w}\right)^2 \\ \{9\} & 0.96 \leq \dfrac{X_1}{X_2} \leq 3.22 \\ \{10\} & 1 \leq \dfrac{X_4}{X_5} \leq 1.79 \\ \{11\} & 17.08 \leq \dfrac{X_1}{X_4} \leq 62.34 \\ \{12\} & 9.41 \leq \dfrac{X_2}{X_5} \leq 27.82 \end{cases} \quad (47)$$

Note that the objective function (Eq. (44)) is the cross-sectional area (Eq. (3)). In this way it can be determined the mass per unit length, by multiplying the area to the specific mass of steel ($7850\ kg/m^3$), which is a constant. The lower is the weight of steel per meter the lower will be the costs for the structure.

The initial point (Eq. (45)) was reached as the middle point between the lower and upper bound limits (Eq. (46)). These limits were obtained as the minimum and maximum variables described in the Fig. 2, according to the profiles in the GERDAU S.A. catalogue.

The function of nonlinear constraints (Eq. (47)) can be split in 4 parts: strength constraints; slender web constraint; transverse stiffeners constraint; geometric constraints. First, the strength constraints are: $\{1\}$, $\{2\}$, $\{3\}$, $\{4\}$, $\{5\}$ and $\{6\}$. Those are the verification of the required strength with the design strength, and the deflection verification, defined at Eq. (13), Eq. (14) and Eq. (15). Second, the slender web constraint {7} was implemented to avoid cases when $\lambda_w > \lambda_r$ in the WLB ultimate limit state. For this specific case it is necessary follow the attachment H from ABNT NBR 8800:2008, however, it wasn't necessary the implementation of this case. Third, the transverse stiffeners constraint {8} was created to eliminate the necessity of transverse stiffeners. Therefore, the constraint enforces a rise of the thickness of the web, in order to control the web shear buckling. Lastly, the geometric constraints ({9}, {10}, {11} and {12}) were used such that the optimized profile could be approached to a proportional solution compared to the GERDAU S.A. catalogue.

3.3 Probabilistic Optimum Design

It was used the Genetic Algorithm for the discrete problem, which uses a probabilistic optimization technique. This technique was used with assistance of the Optimization Toolbox™ from Matlab 2016a. As described in the deterministic optimization, the function that will be optimized is the cross-sectional area of a profile, the same as the Equation 3. For the formulation of the problem it was necessary: fitness function – Eq. (48); lower and upper bounds – Eq. (49); function of nonlinear constraints – Eq. (50).

$$f_{fitness}(X') = \begin{cases} X' \rightarrow X \\ f(X) = 2X_2X_5 + (X_1 - 2X_5)X_4 + X_3^2(4-\pi) \end{cases} \quad (48)$$

$$[\,0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0\,] \leq X' \leq [\,1 \;\; 1 \;\; 1 \;\; 1 \;\; 1 \;\; 1 \;\; 1\,] \quad (49)$$

$$f_{constraints}(X) = \begin{cases} \{1\} & \dfrac{M_{Sd}}{M_{Rd,FLB}} \leq 1 \\ \{2\} & \dfrac{M_{Sd}}{M_{Rd,WLB}} \leq 1 \\ \{3\} & \dfrac{M_{Sd}}{M_{Rd,LTB}} \leq 1 \\ \{4\} & \dfrac{M_{Sd}}{M_{d,res}} \leq 1 \\ \{5\} & \dfrac{V_{Sd}}{V_{Rd}} \leq 1 \\ \{6\} & \dfrac{f_{max}}{f_{lim}} \leq 1 \\ \{7\} & \lambda_w \leq \lambda_r, for\ WLB \\ \{8\} & \dfrac{a}{h} > 3 \;\; or \;\; \dfrac{a}{h} > \left(\dfrac{260}{h/t_w}\right)^2 \end{cases} \quad (50)$$

For this optimization problem with discrete variables, it was necessary change the variable, in order to meet the Matlab function ga and turn the problem into a discrete optimization. This change of variable is symbolized inside the fitness function (Eq. (48)). The variable X' is a vector with 7 cells, and each cell receives only binary numbers (0 or 1). So, each binary vector with 7 cells represents an integer greater than or equal to zero. Thus, this vector will be converted in an integer number, which will represent the position of the beams profiles in the catalogue. In addition, note that for 7 cells the maximum number that can be reached is 127, and the catalogue has just 88 profiles. In this case, every time that the ga function choose a binary number that are higher than 88, it will automatically get the higher possible solution, which is in the 88th position in the catalogue, in other words, it will get the last profile. Therefore, the problem will be a truly discrete problem, where all the possible profiles will be limited to the GERDAU S.A. catalogue.

The lower and upper bounds (Eq. 49) are binary vectors with 7 cells. This vector represents the limits for the possible optimum solution. Note that the integer for the lower bound is 0 and for the upper bound is 127. However, the GERDAU S.A. catalogue has only 88 profiles and the upper bound limit represents the number 127. In this way, the finiteness function will return the 88th position in the catalogue for individuals with the binary that represents numbers greater than 89 until 127.

The function of nonlinear constraints (Eq. 50) follows the same format as defined in the deterministic optimization (Eq. (47)). However, the probabilistic optimization does not have geometric constraints, because it has discrete variables.

Observe that all the optimization with Genetic Algorithm will be made using a binary variable. Therefore, it was used an initial population equal to a binary matrix. This matrix has 88 lines, where each line is a vector with 7 cells and represents a profile in the catalogue. So, the initial population will include all the possible solutions for the problem. However, this process is a little bit slow. Then, it was proposed a maximum number of generations, equal to 25 and a maximum number of stall generations, equal to 20, in order to speed up.

4 COMPARATIVE EXAMPLES

4.1 Graphical User Interface

The interface was developed using the Matlab 2016a GUIDE (Graphical User Interface Development Environment). In this GUI it is possible to verify a profile and also optimize the best profile due the loads in the beam. In the Fig. 3 there is an example of the beam B4 with the following inputs: dead load of 12 kN/m plus the self-weight and the live load of 9 kN/m; elastic modulus of steel of 20.000 kN/cm^2; steel yield stress of 34.5 KN/cm^2; length of the beam of 8.5 m; hot-rolled profile; no continuous lateral bracing.

As an example for the verification, it was chosen the profile W 460 x 97.0. Note in the Fig. 3 that the LTB Limit State wasn't met, because the required bending moment is higher than the design bending moment. Therefore, the GUI shows an error message and the Limit State that wasn't met, shows in red.

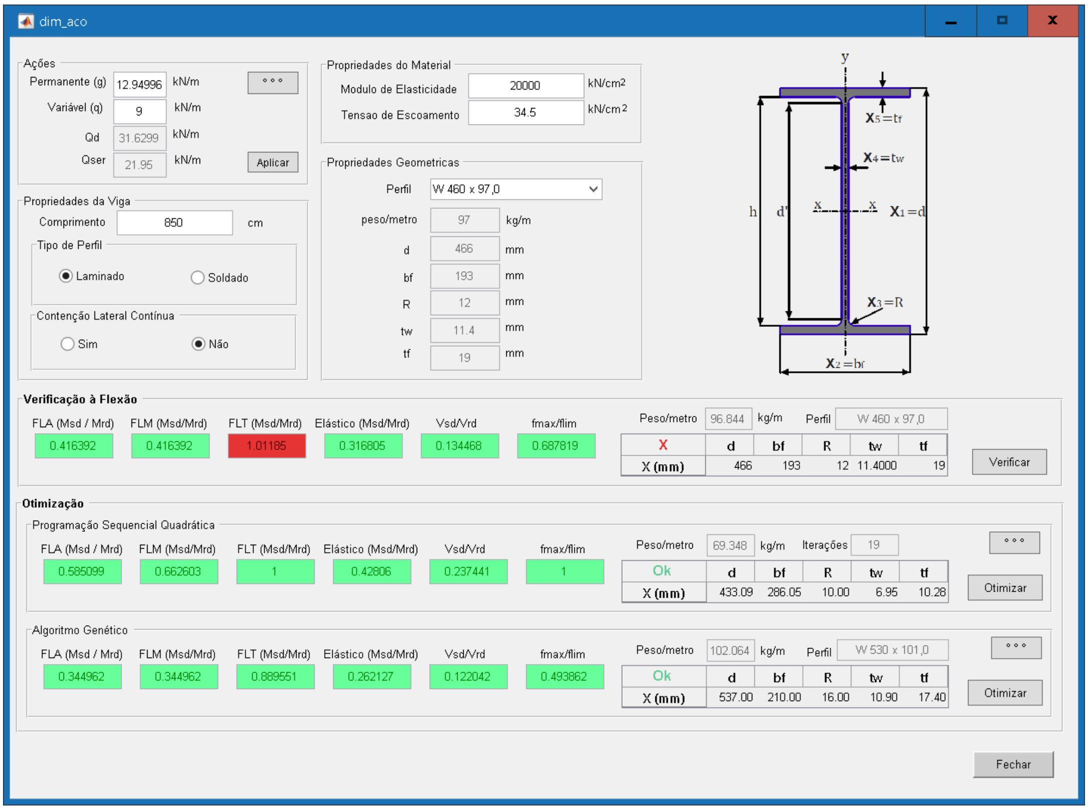

Figure 3. Graphical User Interface for I-section beams, in Portuguese version (Beam B4).

The load combination was done according to the Brazilian standard ABNT NBR 8681. Fig. 4 illustrates a load combination window that can be open inside the Loads Panel allowing the user to classify the loads according to the ABNT NBR 8681. For the comparative analysis and computer program validation it was used the same configuration in the Fig. 4.

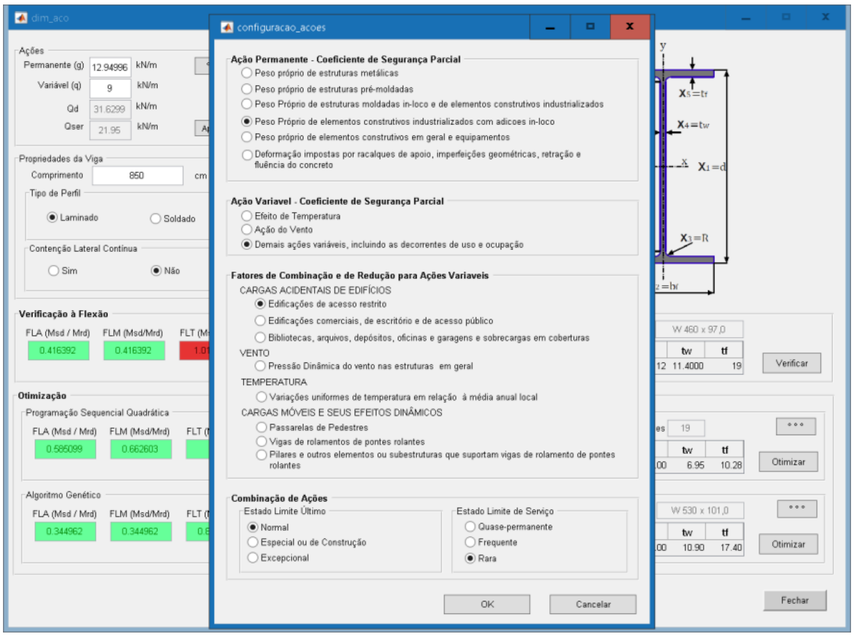

Figure 4. Load Configuration for the item 4.2, in Portuguese version.

There is an option in the optimization panel to configure each optimization technique for the computer program (Fig. 5). The data input for the optimization windows were done using the Optimization Toolbox™ from Matlab 2016a as reference for the graphical design. Figure 5 shows the windows for the optimization panel.

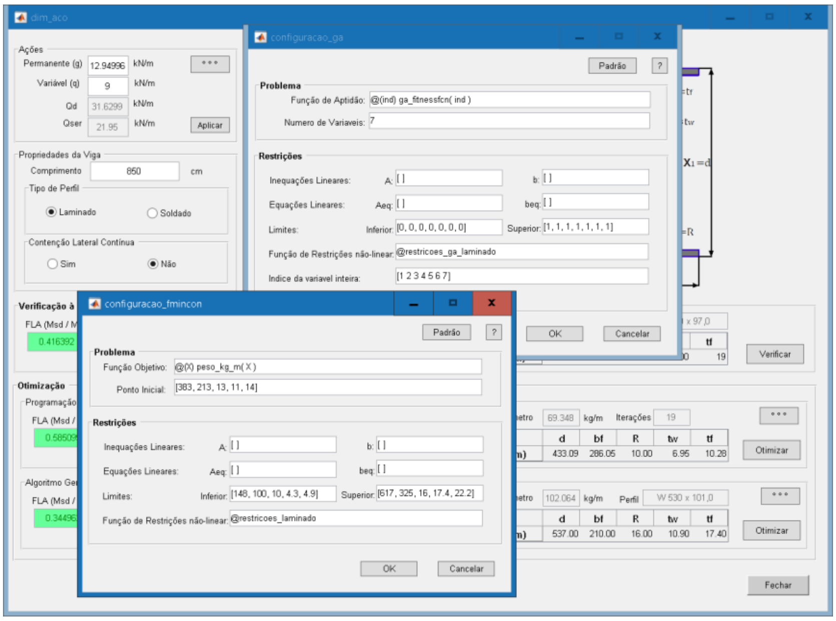

Figure 5. Windows for the optimization panel configuration, in Portuguese version.

4.2 Comparative Analysis and Program Validation

As Lubke (2016), it will be done a comparison with the developed computer program with commercial software, for a set of beams subjected to the same load combination, and increasing the length of the beam. The set was composed by 15 beams (Fig. 1), subjected to a dead load of 12 kN/m and a live load of 9 kN/m, plus the self-weight of the beam. The lengths of the beams were increased with an increment of 0.5 m for each beam, and the last 2 beams (B14 and B15) have continuous lateral bracing.

Firstly, the beams were designed in the commercial software, CYPECAD, and compared to the discrete optimization, which uses the Genetic Algorithm. Table 1 shows the results for the CYPECAD commercial software and for the Genetic Algorithm (GA).

Table 1. Discrete optimization comparison between CYPECAD and GA

Beam *[V#]*	**Length** *[m]*	**Lateral Bracing** *[yes/no]*	**CYPECAD** *[profile]*	**GA** *[profile]*
B1	7	No	W 360 x 64	W 360 x 64
B2	7.5	No	W 360 x 79	W 360 x 79
B3	8	No	W 460 x 89	W 460 x 89
B4	8.5	No	W 530 x 101	W 530 x 101
B5	9	No	W 530 x 109	W 530 x 109

B6	9.5	No	W 610 x 125	W 610 x 125
B7	10	No	W 610 x 140	W 610 x 140
B8	10.5	No	W 610 x 140	W 610 x 140
B9	11	No	W 610 x 155	W 610 x 155
B10	11.5	No	W 610 x 155	W 610 x 155
B11	12	No	W 610 x 155	W 610 x 155
B12	12.5	No	W 610 x 174	W 610 x 174
B13	13	No	W 610 x 174	W 610 x 174
B14	13.5	Yes	W 610 x 155	W 610 x 155
B15	14	Yes	W 610 x 174	W 610 x 174

Note that CYPECAD has the same GERDAU S.A. catalogues, which became easy to compare the results. Also, the results were the same for all the beams.

In addition, some results were given in mass per unit length, which is basically the objective function (cross-sectional area) times the specific mass of steel ($7850\ kg/m^3$). Table 2 gives the comparison of the mass per unit length (kg/m) for the commercial software (CYPECAD), Genetic Algorithm (GA) and Sequential Quadratic Programing (SQP).

Table 2. Comparison of optimized weights (kg/m) – CYPECAD, GA and SQP

Beam	CYPECAD	GA	SQP
B1	64.13	64.09	51.12
B2	79.44	79.44	57.01
B3	89.57	89.57	63.08
B4	102.05	102.06	69.35
B5	109.66	109.66	75.92
B6	125.68	125.70	82.76
B7	140.75	140.77	89.91
B8	140.75	140.77	99.75
B9	155.51	155.50	110.85
B10	155.51	155.50	122.79
B11	155.51	155.50	135.70
B12	174.90	174.89	148.01
B13	174.90	174.89	161.29
B14	155.51	155.50	143.17
B15	174.90	174.89	162.38

The continuous design (SQP) reached to masses far smaller than the results from the discrete optimization, near to 28% lighter on average. This happened due the SQP method optimizes each variable independently, allowing the dimensions of a profile reach to values out of the catalogue. Thus, this optimization procedure gives profiles that are complicated to manufacture. Table 3 has all the dimensions for the optimized profiles due to the SQP technique. Even though some profiles do not have the dimensions in the GERDAU S.A. catalogue, those dimensions are close to the profile's dimensions in the catalogue, because of the geometric constraints (Eq. (47)). However, the next profile that meets the dimension criteria of the optimized beam is a heavy section.

Table 3. Results for the SQP method

Beam	**Iteration**	**X** [mm]					**Next Section**
		d	*bf*	*R*	*tw*	*tf*	
B1	17	375.09	243.85	10	6.02	8.77	W 610 x 155
B2	16	394.96	258.17	10	6.34	9.28	W 610 x 155
B3	16	414.25	272.22	10	6.64	9.79	W 610 x 155
B4	19	433.09	286.05	10	6,95	10,28	W 610 x 155
B5	20	451.97	299,86	10	7.25	10.78	W 610 x 155
B6	19	470.81	313.63	10	7.55	11.27	W 610 x 155
B7	18	487.03	325	10	7.81	11.92	W 610 x 174
B8	15	496.09	325	10	7.96	13.68	W 610 x 174
B9	18	527.45	325	10	8.46	15.12	W 610 x 174
B10	20	570.61	325	10	9.15	16.36	W 610 x 174
B11	13	525.89	325	16	10.34	18.48	W 610 x 174
B12	10	537.58	325	16	11.23	20.07	W 610 x 174
B13	9	550.91	325	16	12.18	21.76	W 610 x 174
B14	10	617	325	16	10.35	18.49	*Not Found*
B15	9	617	325	16	11.78	21.06	*Not Found*

As you can see for the last two beams (B14 and B15) it was not found the next section in the catalogue for the optimized *X*, because the highest value of *d* and *bf*, does not belongs to the same profile. Furthermore, the beams B12 and B13 were the only beams that reached to the same solution in all 3 methods.

In order to study the strengths in a normalized verification, it was defined as effective *resistance* the capacity of a profile to resist the loads effectively. For example, if a profile has an effective *resistance* equal to 100%, this means that the required strength is equal to the design strength. Therefore, when the effective *resistance* is higher than 100%, this means that the beam is under an unstable and unsafe condition. So, when the effective *resistance* is below 100%, it is a condition that the required strength is lower than the design strength.

Table 4 has the percentage ratios between the required and design strength. As you can see, the table is divided according to the method and the percentage ratio. The *resistance* is the ability of a profile to withstand the load in an effective way and the *deflection* is the capacity of a profile to deflect due the load in an effective way. For the *resistance* ratio, it was reached to the most critical ultimate limit state for each beam, and for the *deflection* ratio, it was compared the deflection limit with the maximum deflection, due to the serviceability limit state.

Table 4. Comparison of the effective resistance and effective deflection

Beam	CYPECAD		GA		SQP	
	Resistance(%)	*Deflection(%)*	*Resistance(%)*	*Deflection (%)*	*Resistance(%)*	*Deflection (%)*
B1	90.16	95.08	90.10	94.50	100.00	100.00
B2	78.46	92.39	78.41	92.18	100.00	100.00
B3	94.66	62.38	94.59	62.10	100.00	100.00
B4	89.24	49.91	88.96	49.39	100.00	100.00
B5	95.03	54.78	94.94	54.55	100.00	100.00
B6	84.75	44.19	84.67	43.79	100.00	100.00
B7	82.35	45.55	82.28	45.28	100.00	100.00
B8	96.74	52.54	96.67	52.42	100.00	100.00
B9	64.48	52.98	64.44	52.72	100.00	92.69
B10	75.3	60.34	75.25	60.24	100.00	82.90
B11	87.26	68.36	87.21	68.45	100.00	100.00
B12	82.58	68.21	82.53	68.42	100.00	100.00
B13	94.27	76.55	94.22	76.97	100.00	100.00
B14	49.61	96.65	49.61	97.46	52.02	100.00
B15	47.45	95.22	47.45	96.13	49.94	100.00

Note that the results between the commercial software and the GA were very close for all the beams. The average variation in modulus was **0.08%** for the effective *resistance* and **0.22%** for the effective *deflection*.

The results in Table 4 can be seen in the Fig. 5 and Fig. 6, given by a set of bars. Each beam is represented by 6 bars. The 3 higher and thicker bars show the mass per unit length of the beam, for each technique. Inside each thicker bar there is a smaller and thinner bar, which represents the percentage of mass per unit length that is used effectively in the section of the beam. For example, when both bars reach to the same level, it means that the effective use is 100%.

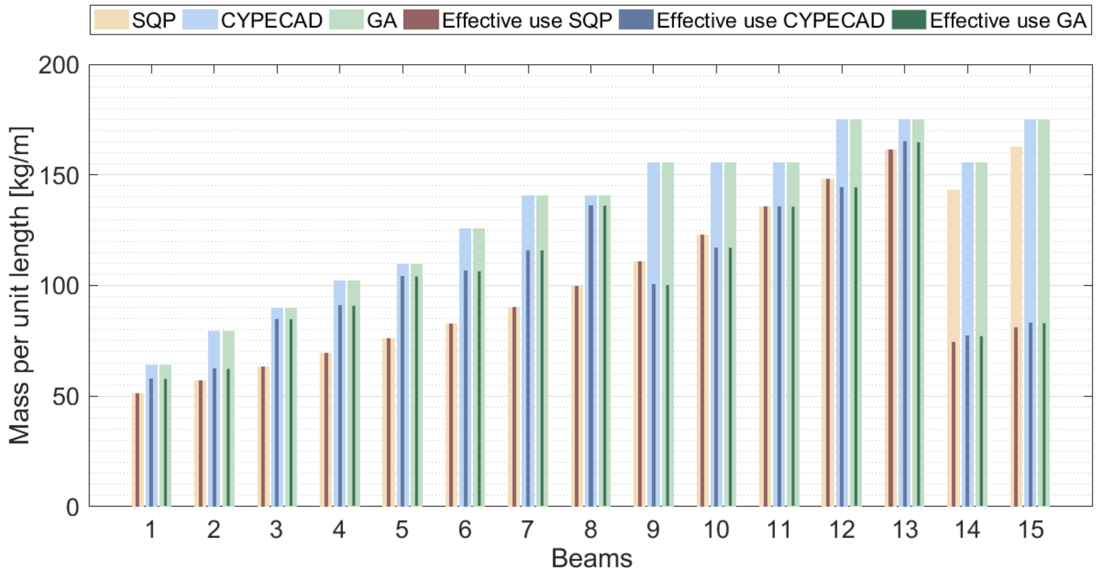

Figure 5. Comparison of the effective resistance for each beam

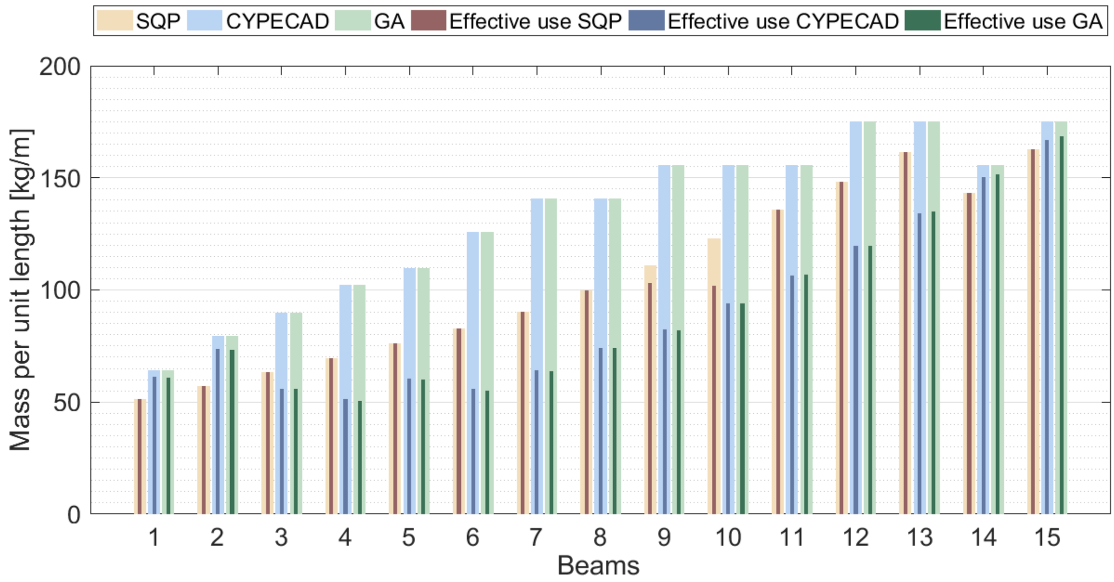

Figure 6. Comparison of the effective deflection for each beam

Observe that the results for the commercial software have the same behavior as the GA method. Plus, comparing the discrete technique with the continuous technique, it is possible to note a considerable difference. The PQS method basically used all the effective *resistance* and *deflection*, differently from the GA and CYPECAD, which used part of the resistance for most of the beams. In addition, the beams with lower lengths (B1 and B2) and the beams with lateral bracing (B14 and B15), the key factor was the *deflection*, and for the other beams were the *resistance*.

5 CONCLUSION

It was proposed a comparison of optimization technics with the CYPECAD commercial software. Also, it was developed an optimum design program to support the research. The computer program provided the expected results, proving the validation of the program.

First, it was possible to show that the genetic algorithm converge with on an average of 7 to 10 generations. On the other hand, the sequential quadratic programing converges with on an average of 16 iterations. Even though the SQP requires more loops to converge, it is faster than the GA, however, the SQP method is a continuous variable optimization, which is hard to manufacture, because it isn't in the catalogues. Also, the sections found in the catalogues for the SQP method were very robust.

Second, the comparison between the GA and the commercial software for the 15 beams showed great results, based on the effective *resistance* and *deflection*. Related to the effective *resistance*, the computer program developed was around **0.09%** less conservative than the commercial software, for beams with no bracing. For the beams with continuous lateral bracing (B14 and B15), the formulation presented **0%** of difference, for the effective *resistance* as well. However, for the effective *deflection*, the results showed **0.32%** less conservative for beams with no bracing. Additionally, for the beams with continuous lateral bracing, it was **0.89%** more conservative. It can be concluded that the formulation for the optimization problem, drew close to the commercial software, justifying the validation of the program.

Lastly, with the computer program created, it will be possible to expand a design procedure for unsymmetrical bending and combined loading. That way, it will be available to handle enough project situations. Moreover, it will be provided more structural profiles, with the purpose of getting more reductions in the consumption of steel in the civil construction.

ACKNOWLEDGEMENTS

The authors would like to thank CNPq, FAPES, PRPPG-UFES, PIVIC and Civil Engineering Department of Federal University of Espírito Santo for all the support.

REFERENCES

Akbari, J., Ayubirad, M. S., 2016. Seismic Optimum Design of Steel Structures Using Gradient-Based and Genetic Algorithm Methods. *International Journal of Civil Engineering*, Iran University of Science and Technology. Springer International Publishing.

American Institute of Steel Costruction, 2005. *ANSI/AISC 360-05*: *Specification for Structural Steel Buildings*. Chicago, Illinois.

Associação Brasileira de Normas Técnicas, 2003. *NBR 8681: Ações e seguranças nas estruturas – Procedimento*. Rio de Janeiro, RJ.

Associação Brasileira de Normas Técnicas, 2008. *NBR 8800: Design of Steel and Composite Structures for Buildings*. Rio de Janeiro, RJ.

Alves, E.C., Vaz, L. E, 2013. Optimum design of plates structures under random loadings, *Revista da Escola de Minas*, Ouro Preto, Vol. 66, pgs 41-47.

Alves, E.C., 2017. *Análise de Sensibilidade e Otimização de Estruturas Submetidas a Vibrações Aleatórias*, Novas Edições Acadêmicas, Mauritus.

CYPECAD®, 2015. *Software for Architecture, Engineering and Construction*. Version 2015.p.CYPE Ingenieros, S.A.

GERDAU®, 2016. *Perfis Estruturais Gerdau – Tabela de Bitolas*, accessed on 16/08/16 <https://www.gerdau.com/br/pt/produtos/catalogos-e-manuais#k=#s=41>

Lubke, G. P., Alves, E. C., Azevedo, M. S., 2017. Dimensionamento Otimizado de Vigas Celulares de Aço. In: *XXXVII Iberto Latin American Congress on Computational Methods in Engineering*, 2017, Revista da Estrutura de Aço. Vol. 6, p 01-29.

MATLAB®, 2016. *Optimization toolbox user's guide*. Natick: Mathworks.

Novelli, L., Alves, E. C., Gomes Filho, H., Garozi, M. J. P., Azevedo, M. S., 2015. Ferramenta Computacional para o Dimensionamento de Estruturas Tubulares Treliçadas. In: *XXXVI Iberto Latin American Congress on Computational Methods in Engineering*, 2015, Rio de Janeiro.

Novelli, L., Alves, E. C., Sias, F. M., Azevedo, M. S., Gomes Filho, H., Garozi, M. J. P., 2015. Dimensionamento Ótimo de Estruturas Tubulares Espaciais Segundo a NBR 8800. In: *XXXVI Ibero-Latin American Congress on Computaional Methods in Engineering*, 2015, Rio de Janiero, RJ.

Pfeil, W., Pfeil, M., 2015. *Estruturas de Aço – Dimensionamento Prático de Acordo com a NBR 8800:2008*, 8º. ed. – Rio de Janeiro, RJ.

Unde, Y., 2016. *Structural Design Optimization of Steel Buildings.* A thesis Presented in Partial Fulfillment of the Requirements for the Degree Master of Science, Arizona State University, Tempe, AZ.