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Automated Design of Steel and Composite Steel-Concrete Beams According to NBR 8800 Using Genetic Algorithms

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Abstract. Technological progress enables precise simulation of complex, slender structures using computational tools. Making use of such tools, a Python routine was developed for the design of steel beams with non-slender webs, covering welded, rolled profiles, and mixed steel-concrete beams, in accordance with the NBR 8800:2008 standard. The routine incorporates a genetic algorithm (PyGad) for discrete parametric optimization, selecting the most suitable profile among commercial options. The weighting function considers parameters such as inertia, mass, modulus of elasticity, radius of gyration, and bending strength, with weights adjusted by the algorithm. The verification of serviceability limit states and vibration frequencies is also part of the process, offering a comprehensive approach to design and optimization. After ensuring compliance with the NBR 8800:2008 standard requirements, it was possible to perform several additional analyses with the selected beam, such as cost, weight/performance ratio, boundary conditions, degree of utilization, as well as comparisons between different profile types and beam models. The case study involved the analysis of distinct beam models, allowing an effective comparison between different types of profiles and their characteristics. The results highlighted the program's ability to provide optimized solutions, considering criteria such as price, weight, boundary conditions and utilization.

Keywords: steel, beams, optimization, algorithms.

1 Introduction

The world has been undergoing significant transformations driven by technological advancements, which have led to the adoption of new techniques in structural engineering, especially due to the increasing slenderness of structures. Among these innovations, the use of steel structures stands out, which, as noted by Fakury [1], has grown significantly in recent years not only in industrial sectors such as warehouses and storage facilities but also in multi-story buildings, offering various advantages. However, this evolution demands continuous research and the development of processes capable of accurately simulating the behavior of complex structural systems, which has become a central focus of the international Structural Engineering community. Alves, Rodrigues, and Breda [2] emphasize that engineering designs have always sought to achieve maximum efficiency in the use of resources.

In recent decades, the need for innovation in structures and technologies has driven the development of computational tools applied to engineering. Such tools, according to Fernandes [3], must accurately represent structural behavior, while Arpini [4] highlights the importance of economic feasibility in optimized solutions.

In this context, the use of programming languages has become common among engineers due to their effectiveness in solving analytical problems. This study adopted the Python language, recognized for its simplicity and wide technical acceptance.

Structural design, historically based on standards and empirical judgment, is an iterative and time-consuming process. Contemporary structural optimization techniques aim to systematize it, leveraging advances in materials such as reinforced concrete and steel structures, targeting efficiency and cost reduction without compromising safety. For this purpose, modeling must faithfully reflect real service conditions, as pointed out by Fiorotti [5].

One area that stands out in this context is the genetic algorithm, whose application, according to Kameshki [6], can lead to more economical and safer design solutions. Lopes and Miguel [7] explain that the genetic algorithm was initially proposed by John Holland and is based on Darwin's theory of evolution. Each individual represents a possible solution to the design problem and is evaluated based on performance criteria. The fittest individuals are selected to survive, while the others are discarded. The survivors crossbreed, generating new solutions through reproduction. Thus, by combining a computational base with structural optimization and genetic algorithms, it is possible to perform rapid and efficient analyses of different steel profiles, verifying whether such materials meet national and international regulatory requirements regarding structural and vibrational performance.

The main objective of this work is to develop a computational routine using the Python language for the design of steel beams with non-slender webs, with singly symmetric and doubly symmetric sections, including welded, rolled profiles, and steel-concrete composite beams, according to the criteria of NBR8800:2008, using the PyGad genetic algorithm.

The specific objectives of this study are:

- To develop a Python code to automatically verify the provisions of NBR8800:2008 [8] for steel and composite beams subjected to simple bending;
- To integrate the verification routine with the PyGad genetic algorithm, defining its parameters and applying the appropriate methodology described throughout this work.

2 Materials and Methods

Obtaining the results, a code will be developed in the Python language, incorporating, among other methods, the optimization technique based on Genetic Algorithms, as well as the design procedures established by the NBR 8800:2008 standard, applicable to steel and composite steel-concrete beams. Genetic algorithms use a parallel, structured, and probabilistic approach aimed at identifying regions of the search space with higher "fitness," that is, points where the function to be minimized (or maximized) presents more advantageous values. Although they involve random elements, these searches do not follow entirely random paths, as they utilize historical data from the evaluated population to explore new promising regions. This strategy is conducted through iterative processes called generations. In each of these iterations, selection and reproduction mechanisms are applied to a set of candidates, whose number may vary according to the complexity of the problem and the computational resources available.

In this study, the initial population was composed from a table (GERDAU) containing various types of structural profiles, such as W, HP, CE, CVE, VE, CS, CVS, VS, and VSM profiles, with varied dimensions and properties. These profiles were organized into two distinct tables: one containing 537 singly symmetric profiles and another with 15 doubly symmetric profiles.

The population is randomly generated with n individuals, each representing a potential solution within the search space. Then, the fitness of each individual is evaluated through the objective function, which takes into account the defined design requirements, with its general formula exemplified below in Equation (1):

$$f(y) = \sum x_n w_n \tag{1}$$

For this work, the value of "x" will be the parameter being analyzed at that moment for that profile, and the value of "w" will be the weight values that the program will calculate. Thus, four parameters will be considered to be taken into account in the fitness function (in addition to the boundary conditions). These will be called the "function inputs," that is, the variables that enter the function.

The first parameter used was the minimum moment of inertia (Imin), previously obtained by Equation (2) below:

$$I_{mín} = \frac{5.q.L^4}{384.Ea.fm} \text{ ou } I_{mín} = \frac{P.L^4}{48.Ea.fm} \quad (2)$$

Where: "q" is the distributed load; "P" the concentrated load; "Ea" the longitudinal modulus of elasticity; "L" the span length; and "fm" the maximum deflection. According to Fakury, the value of the maximum deflection is calculated based on several factors, considering: closing purlins with displacement parallel to the closing plane, whose maximum displacement is calculated as the effective width divided by 180; closing purlins with displacement perpendicular to the closing plane, with maximum displacement calculated as the effective width divided by 120; roof purlins under rare service combinations, using variable loads acting in the same direction as the permanent load, with maximum displacement calculated as the effective width divided by 180; roof purlins under rare service combinations, considering only variable loads acting opposite to the permanent load, with maximum displacement calculated as the effective width divided by 120; roof beams, whose maximum displacement is calculated as the effective width divided by 250; floor beams, with maximum displacement calculated as the effective width divided by 350; and beams supporting columns, with maximum displacement calculated as the effective width divided by 500.

The second parameter to be taken into account was the minimum elastic section modulus (Wmin), obtained by Equation (3) below:

$$W_{min} = \frac{Msd}{fy} \quad (3)$$

Where: "fy" is the steel yield strength and "Msd" is the design bending moment.

The third parameter to be considered was the minimum radius of gyration (rmin), obtained by Equation (4) below:

$$r_{min} = \frac{k.L}{200} \quad (4)$$

Where: "k" is the constant determined by the boundary condition and "L" is the span length.

The fourth and final parameter to be considered was the minimum weight (Pmin), obtained by the formula (5) below:

$$P_{min} = \rho.Amin \quad (5)$$

Where the minimum area is obtained by the following formula (6):

$$A_{min} = \frac{Imin}{rmin^2} \quad (6)$$

Where: "ρ" is the specific mass of steel, taken as 7850 kg/m³.

Thus, the fitness function, shown in Equation (7), obtained for this work was:

$$f(y) = x_1w_1 + x_2w_2 + x_3w_3 + x_4w_4 \quad (7)$$

Since each parameter used had a specific unit, it was necessary to make the function dimensionless. To do this, all relevant parameters were divided by their respective minimum values, as described in the formula below, where each "solution" corresponds to a parameter used in the fitness function, shown in Equation (8):

$$f(y) = \frac{ry\ .solution\ [3]}{rmin} + \frac{MASSA\ LINEAR.solution\ [2]}{Pmin} + \frac{Ix.solution[0]}{Imin} + \frac{Wx.solution\ [1]}{Wmin} \quad (8)$$

After that, the algorithm will calculate the weights of the weighting function. Thus, with the weights from the first run of the genetic algorithm, it will calculate f(y) profile by profile, where for profile 1, the following fitness function applies, shown in Equation (9):

$$f(y)_{p1} = \sum x_{pn}^{i} w_i = x_{p1}^{1} w_1 + x_{p1}^{2} w_2 + x_{p1}^{3} w_3 + x_{p1}^{4} w_4 \quad (9)$$

For profile 2, the following fitness function applies, shown in Equation (10):

$$f(y)_{p2} = \sum x_{pn}^{i} w_i = x_{p2}^{1} w_1 + x_{p2}^{2} w_2 + x_{p2}^{3} w_3 + x_{p2}^{4} w_4 \quad (10)$$

And so on, with the general formula described below, formula (11):

$$f(y)_{pn} = \sum x_{pn}^{i} w_i = x_{pn}^{1} w_1 + x_{pn}^{2} w_2 + x_{pn}^{3} w_3 + x_{pn}^{4} w_4 \quad (11)$$

It is important to note that in the calculation of the function f(y) for each profile, the weights (Wi), calculated in the first and only run of the program, remain unchanged. At this stage, the fittest individuals of the current generation are selected. These individuals are used to generate a new population through crossover.

For this, it is necessary to adjust some parameters in the genetic algorithm, such as the fitness function, which represents the degree of adaptation of an individual to the environment in which it is inserted. In computational terms, this metric indicates how effective a candidate solution (individual) is in solving the proposed problem (environment). It is also essential to define the number of generations, which is directly related to the population size and the computational time available for running the algorithm. In this study, the value of 200 was adopted for this parameter.

The next step consists of establishing the types of crossover and mutation to be applied. These operators ensure that the new generation is composed of novel individuals, while maintaining, to some extent, inherited characteristics from their parents. In this way, the population diversifies while preserving adaptive traits acquired in previous generations. For this work, the "single_point" crossover was selected, in which a crossover point is defined, and the genetic information from the parents is exchanged starting at this point. Thus, the genes before this point from one parent are combined with the genes after this point from the other parent. Regarding mutation, a random alteration was chosen, allowing the diversification of the new generation through spontaneous genetic changes.

Subsequently, with the calculated values of f(y) already available, a sorting in ascending order of the profiles is performed according to the values of the previous function, to verify compliance with the set of restrictions of the NBR 8800 standard.

3 Results and Discussion

This section aims to discuss the results obtained from the implementation of the genetic algorithm in three different scenarios. In all cases, the maximum displacement calculation considered closing purlins with displacement parallel to the closing plane, and their application was for residential and office floors. The steel strength considered was 350 MPa, the longitudinal modulus of elasticity was 200,000 MPa, and the transverse modulus of elasticity was 77,000 MPa. The modification factor for the non-uniform bending moment diagram (Cb) was used as 1, since NBR8800:2008 establishes this value for all cases to make the problem more conservative. Lateral bracing was also not used.

3.1 Profiles with different boundary conditions

For this scenario, the same beam was considered, with the same length and load, but different boundary conditions. The boundary conditions used were simply supported beam, pinned at one end and fixed at the other, fully fixed beam, and cantilever beam. Profiles with two axes of symmetry were considered, a span of 10 m, and a concentrated load of 12 kN at the mid-span section.

Considering the algorithm, the utilization percentage of each selected profile was calculated, taking into account M_{sd} (design bending moment), V_{sd} (design shear force), $M_{R,FLM}$ (resistant moment for lateral-torsional buckling of the flange), $M_{R,FLA}$ (resistant moment for lateral buckling of the web), $M_{R,FLT}$ (resistant moment for lateral-torsional buckling), and V_{Rd} (resistant shear force). The results are shown in Figure 1 below.

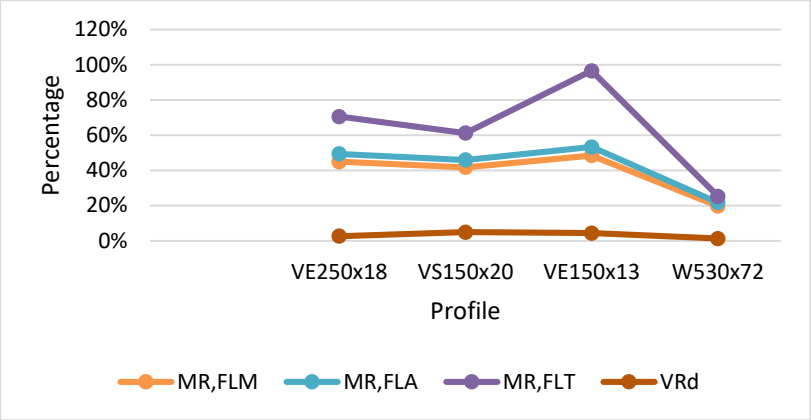


Figure 1. Graph of profile utilization percentage with change in boundary condition

Using the data for each profile, it is also possible to calculate its weight and, consequently, its price. The reference price used was from SINAPI (2023), set at R$9.18/kg. The results are in the Table 1.

Table 1. Price for beams with different boundary conditions

Conditions	Profile	Weight (Kg)	Price (R$)
Simply supported	VE250x18	180	1652.40
Pinned at one end and fixed at the other	VS150x20	200	1836.00
Fixed	VE150x13	130	1193.40
Cantilever beam	W530x72	720	6609.60

In conclusion, it can be inferred that the most expensive and consequently the heaviest beam was the cantilever beam, with a cost of R$6,609.60, followed by the beam pinned at one end and fixed at the other at R$1,836.00. Next comes the simply supported beam at R$1,652.40, and finally, the least expensive being the fully fixed beam, costing R$1,193.40. This result is due to the fact that the cantilever beam experiences greater displacement at the free end, so to prevent this, a more robust - and consequently more expensive - profile is required.

3.2 Load and beam length combinations

The next beam problem was based on the work of Senouci and Al-Ansari [9], in which a combination of different loads and different beam lengths was analyzed. In other words, with a distributed load of 12 kN/m, the span length was varied five times, using 1 m, 3 m, 5 m, 7 m, and 9 m. The load was then increased to 22 kN/m, and the span was again varied five times, using the same dimensions as before. The same process was repeated with a load of 32 kN/m. With the corresponding profiles, it is possible to perform a cost analysis for each one. The results can be seen in Figure 2 below.

With the different combinations, the graph shows that the greater the load and the longer the span, the more expensive the beam becomes.

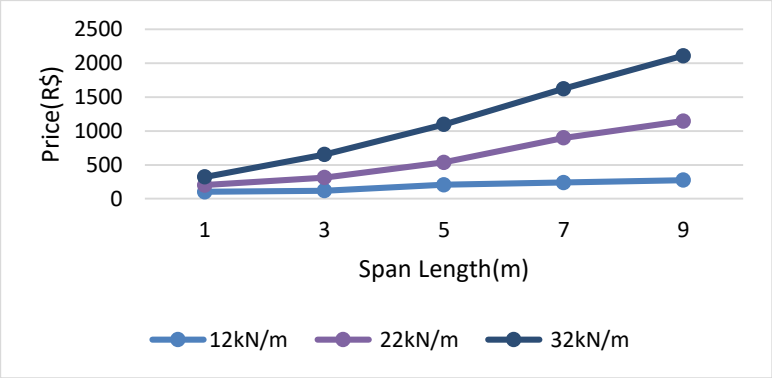


Figure 2. Graph of profile pricing with different loads and spans

3.3 Composite beam

A study was also conducted on the composite beam, using both singly symmetric and doubly symmetric profiles, to allow for a comparison between them. The beams used were simply supported, with a distributed load of 5 kN/m and a span of 6 m. The profile selection was carried out using a genetic algorithm, which employs a function that favors individuals with higher fitness. This value is determined based on previously defined weights. The degree of interaction (α), resulting from the combination of a steel beam with a concrete or composite slab, was 0.40. The selected profiles, along with their respective function values, are presented in Tables 2 and 3 below, along with the "n" value of connectors and their quantities. The profile identified as optimal is highlighted in Tables 2 and 3 below.

Table 2. Y function for singly symmetric profiles considered for the simply supported composite beam

Perfil	Y	n	Qtd
VSM350x36	85.98	8.13	8
VSM350x38	90.10	8.47	8
VSM400x42	125.60	9.39	9
VSM400x46	143.79	10.48	10
VSM450x59	186.09	13.28	13
VSM450x68	221.89	15.42	15
VSM500x71	259.41	15.98	16

Table 3. Y function for doubly symmetric profiles considered for the simply supported composite beam

Perfil	Y	n	Qtd
VS400x38	129.06	8.61	9
VS400x39	137.21	8.92	9
W360x51	138.19	11.51	12
VS350x51	153.47	11.61	12
CVS300x79	169.82	17.92	18
HP310x79	171.82	17.76	18
CVS300x85	174.01	19.32	18

The following data are obtained from the program for the selection of the optimal singly symmetric profile: Parameters of the best solution: [2.12126987e+00, 1.04638820e+01, -3.90150750e-04, 1.99153049e+00]; Fitness value of the best solution: 26.92921810534337; Predicted output based on the best solution: 2999.96286561325. Data for the selection of the optimal doubly symmetric profile are also obtained: Parameters of the best solution: [21.88724792, 10.73862849, -0.02308464, 7.64660767]; Fitness value of the best solution: 11.356871675733231; Predicted output based on the best solution: 3000.088052416946.

With the optimal profile selected, it is also possible to price the composite beam. Considering the slab with a length of 6 m, a width of 2.25 m, and a thickness of 0.12 m, its volume can be calculated. Thus, with all the available data, it is possible to calculate the cost of each necessary material, considering steel at R$9.18 per kilogram, concrete at R$329.67 per cubic meter, and bolts of ASTM A307 with a diameter of 19 mm, with each unit priced at R$9.50 according to SINAPI (2023). Accordingly, the prices are inferred in Table 4 below.

Table 4. Composite Beam Pricing

	VSM 400x46	**VS 350x51**
Preço perfil (R$)	422.28	468.18
Preço parafuso (R$)	95.00	114.00
Preço concreto (R$)	534.10	534.10
Preço total (R$)	1051.38	1116.28
% concreto no total	50.80%	47.85%

It can therefore be said that the singly symmetric profile in the composite beam was less expensive, as it uses less material where it is not structurally necessary and is lighter, which reduces transportation and assembly costs. The concrete price also has a 50.80% influence compared to 47.85% for the doubly symmetric profile.

4 Conclusions

The use of genetic algorithms in structural engineering represents a significant advancement in the pursuit of more efficient, economical, and safe solutions. Inspired by the principles of natural evolution, these algorithms are capable of exploring large solution spaces, finding optimized structural configurations that simultaneously meet multiple design constraints. Their application enables the automation of the design process, reduces development time, and minimizes structural costs without compromising performance or safety. Thus, genetic algorithms establish themselves as a powerful computational tool in the context of structural optimization, especially when integrated with programming languages such as Python and used in conjunction with technical standards like NBR 8800.

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