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Optimum design of prestressed steel beams via genetic algorithm

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Abstract

The objective of this article is to present an optimization problem formulation to reduce the total structural cost of prestressed doubly-symmetric and monosymmetric I-shaped steel simply supported beams with straight tendons. The optimization problem was implemented via MATLAB's native Genetic Algorithm. The validation and evaluation processes adopted two examples from literature. The design method follows the Brazilian standard NBR 8800:2008 for the Ultimate and Serviceability Limit States. The best result was found for a monosymmetric case by up to 20.00% and 25.70%. Saving in material weight and installation of tendons, without exceeding the security limits, was also effective. Furthermore, the results presented an efficient alternative for structural engineering, providing a significant model for similar analyzes.

Keywords: prestressing; steel beams; genetic algorithm; optimization.

1. Introduction

Although steel structures have more advantages than other materials, their cost is a negative point. Composite materials as well as new design methods can be developed to minimize such a factor.

It is well known that prestressed steel could provide economic advantages over traditional techniques. In this respect, such technique has been involving research for improvement since Belenya (1977). Furthermore, Belletti and Gasperi (2010) noticed the number of deviators, such as prestressing tendons and theirs position, as critical design variables that require attention, aiming for better beam performance.

Design methods must be as accurate as possible to guarantee structural safety. Therefore, a higher number of variables, combinations, and conditions are involved. Moreover, the trial and error to obtain the lowest cost of prestressed steel structures requires computational approaches.

Many studies have shown the Genetic Algorithm (GA) optimization technique as a powerful tool to improve the design on structural engineering (Agrawal, Chandwani and Porwal (2013), Kociecki & Adeli (2015), Yldirim & Akcay (2019), Martinelli & Alves (2020), Skoglund, Leander & Karoumi (2020)). The GA was proposed by Holland (1992) based on the Charles Darwin's Theory of Evolution. The search and combination processes allow the algorithm to find a result without exceeding determined conditions, called constraint functions.

GA also presents a high capacity for working with multiple constraints without elevated computational cost. Dealing with this type of problem was approached by Tang, Tong and Gu (2005). Mixed coding, i.e., integer and continuous variables, successfully showed results on a truss design optimization.

Kripakaran, Hall and Gupta (2011) proposed a GA formulation employing discrete decision variables. Furthermore, a search space was delimitated to limit the GA combinations. Such methodology is deeply explained by Rajeev & Krishnamoorthy (1997) and Gupta *et al.* (2005) aiming for a higher computational performance.

The Spanish, European and American codes were adopted for the optimization of steel structures by Prendes-Gero *et al.* (2018) . The GA was implemented to follow a 144 cross-section database and determine the optimum value for a three-story steel building. Results demonstrated the capacity of the algorithm on the internationals building design codes. Moreover, the researchers pointed out the use of discrete variables to obtain better results.

Taiyari, Kharghani and Hajihassani (2020) compared four metaheuristic optimization techniques in the design of pile wall retaining systems: Genetic, Particle swarm optimization, Bee, and Biogeography-based algorithms. The reduction on the total structural cost was selected as the objective function. OpenSees software and the MATLAB platform were used for coding. The GA proved to be able to reduce the objective function.

Alves & Ramos (2021) proved the GA effectiveness of the weight reduction on a steel-concrete composite beam. MATLAB's native GA was also adopted, using its GUI platform. The Ultimate and Serviceability Limit States were followed by the Brazilian standard NBR 8800:2008. Small spans were analyzed, i.e., from 5 to 16 meters. The objective function consists of multiple constraints.

Recently, Mageveske *et al.* (2021) have shown the possibility of savings in material weight and total structural cost on doubly-symmetric I-shaped steel beams. The researchers optimized the Ultimate and Serviceability Limit States following the Brazilian standard NBR 8800:2008.

This article presents an optimization problem for prestressed I-shaped simply supported steel beams. The design model is in accordance with the standard NBR 8800:2008 and was implemented via MATLAB's platform using the GUI tool to generate an interactive graphical interface. To solve the optimization problem, this program makes use of MATLAB's native GA. Both are monosymmetric, such that their being doubly-symmetric, presented significant economic results.

2. Optimization problem formulation

The optimization problem considered shapes as illustrated by Figure 1. Therefore, the number of prestressed tendons (n_t), the depth of cross-section (d), and the flange widths (b_{fs} and b_{fi}), were considered as integer variables. Flange thicknesses (t_{fs} and t_{fi}) and web thickness (t_w) were considered as continuous variables, i.e., a hybrid formulation. Notice that doubly-symmetric cases are particular cases when $b_{fs}= b_{fi}$ and $t_{fs}= t_{fi}$.

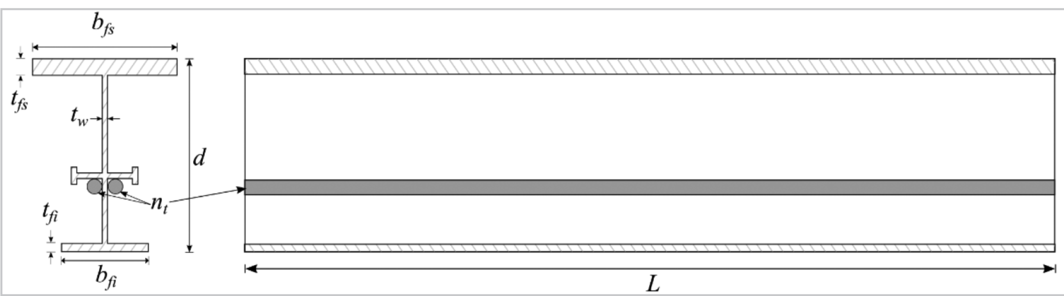

Figure 1 – General cross-sectional variables.

2.1 Objective function

The objective function must reduce the total structural cost – Equation (1). Therefore, the volume of steel, the number of prestressed tendons, and its anchorage were considered.

$$f(x) = (Ct_s \cdot A_s + Ct_t \cdot n_t \cdot \mu_t) \cdot L + (n_t \cdot Ct_{ti}) \quad (1)$$

Where: Ct_s is the cost of steel [R\$/m³]; As is the cross-section area [m²]; Ct_t is the tendon's cost [R\$/kN]; nt is the number of tendons; μt is the specific weight of the tendons [kN/m]; L is the length of span [m]; and, Ct_{ti} is the tendon's anchorage cost [R\$]. The input values are described in Table 1. The presence of deviators naturally alters the objective function, so that the length of the tendons will not be equal to the span.

Table 1 – Input values.

Diameter	9.5 mm	15.2 mm
Ct_s	R\$ 12.88	
Ct_t	R\$ 12.69	
Ct_{ti}	R\$ 125.66	R\$ 158.65
μ_t	0.004158 kN/m	0.012152 kN/m

2.2 Constraint functions

The constraint functions, Equations 2 to 18, followed the Brazilian standard NBR 8800:2008. The design criteria satisfy both serviceability and strength requirements. Notice that C(7), C(8), and C(10) are coded as an if-else statements due to the cross-sectional shape, i.e., doubly-symmetric or monosymmetric.

$$C(1): M_{sd} / M_{rd} - 1 \leq 0 \tag{2}$$

$$C(2): M_{sd_e} / M_{rd} - 1 \leq 0 \tag{3}$$

$$C(3): V_{sd} / V_{rd} - 1 \leq 0 \tag{4}$$

$$C(4): N_{sd} / N_{rd} - 1 \leq 0 \tag{5}$$

$$C(5): \delta_{tot} / \delta_{lim} - 1 \leq 0 \tag{6}$$

$$C(6): \delta_{e} / \delta_{lim} - 1 \leq 0 \tag{7}$$

$$C(7): \left(\frac{N_{sd}}{N_{rd}} + \frac{8}{9} \right) \cdot \left(\frac{N_{sd_e}}{N_{rd}} \right) - 1 \leq 0, \frac{N_{sd}}{N_{rd}} \geq 0.2 \tag{8}$$

$$C(7): \left(\frac{N_{sd}}{2\,N_{rd}} \right) + \left(\frac{M_{sd}}{M_{rd}} \right) - 1 \leq 0, \frac{N_{sd}}{N_{rd}} \geq 0.2 \tag{9}$$

$$C(8): \left(\frac{N_{sd}}{N_{rd}} + \frac{8}{9} \right) \cdot \left(\frac{M_{sd}}{M_{rd}} \right) - 1 \leq 0 \tag{10}$$

$$C(8): \left(\frac{N_{sd}}{2\,N_{rd}} \right) + \left(\frac{M_{sd}}{M_{rd}} \right) - 1 \leq 0 \tag{11}$$

$$C(9): 1 - 4 \left(\frac{b_f}{d} \right) \leq 0 \tag{12}$$

$$C(10): \frac{3}{2} \left(\frac{b_f}{d} \right) - 1 \leq 0 \tag{13}$$

$$C(11): \left(\frac{4}{\sqrt{(h / t_w)}} \right) / 0.76 - 1 \leq 0 \tag{14}$$

$$C(12): 1 - \left(\frac{4}{\sqrt{(h / t_w)}} \right) / 0.35 \leq 0 \tag{15}$$

$$C(13): \sigma_t / f_y - 1 \leq 0 \tag{16}$$

$$C(14): \sigma_c / f_y - 1 \leq 0 \tag{17}$$

Where: M_{sd} is the design bending moment [kNm]; Mrd is the design bending moment resistance [kNm]; M_{sd},e is the prestressing bending moment [kNm]; Vsd is the design shear force [kN]; V_{rd} is the design shear resistance [kN]; N_{sd} is the design axial force [kN]; N_{rd} is the design axial load resistance [kN]; δ_{tot} is the total vertical displacement [mm]; δ_{lim} is the maximum vertical displacement [mm]; δ_{tot}, e is the vertical prestressing displacement [mm]; d is the depth of a cross-section [mm]; b_f is the flange width [mm]; h is the depth of a web [mm]; t_w is the web thickness [mm]; σ_t and σ_c are the maximums tensile and compressive strength [kN/m²], respectively; and, f_y is the yield strength [kN/m²].

The C(1), C(2), C(3) and C(4) delimits the maximum efforts of steel considering its resistance. C(5) and C(6) evaluate the displacements on the Serviceability and Ultimate Limit States. C(7) (prestressing time) and C(8) (In service) limits the combining bending. C(9), C(10), C(11), and C(12) govern the geometric properties to avoid buckling. C(13) and C(14) evaluate the yield strength over the limits of compression and tension. Therefore, the optimization problem proposed was solved via MATLAB's native GA.

In the analysis method, the required forces were estimated from the equilibrium equations – Table 2. The tendons eccentricity herein defined as e is considered on the pretension load. The distance from the left support is indicated by *a*.

Table 2 – Relationships for estimating the internal forces.

Internal forces	Distributed load (q)	Concentrated load (P)	Pretension load (F)
Bending moment	$\frac{qL^2}{8}$	$\frac{Pa}{2}, a < \frac{L}{2}$ $\frac{P(L-a)}{2}, a \leq \frac{L}{2}$	Fe
Shear force	$\frac{qL}{2}$	$\frac{Pa}{L}$	-
Normal force	-	-	F

3. Numerical analysis

Two design examples from literature were analyzed: A Finite Element approach via ANSYS, presented by Abbas *et al.* (2018); and (ii) a traditional design presented by Ferreira (2007), following the Brazilian standard NBR 8800:1986.

Both the examples adopted the characteristic tensile strength of tendons (f_{ptk}) equal to 1900 MPa, as well as the coefficient modification value for non-uniform bending moment diagram (C_b) equal to 1. The examples consist of simply supported beams due to comparison with literature – Figure 2. Different boundary conditions can be straightforwardly employed.

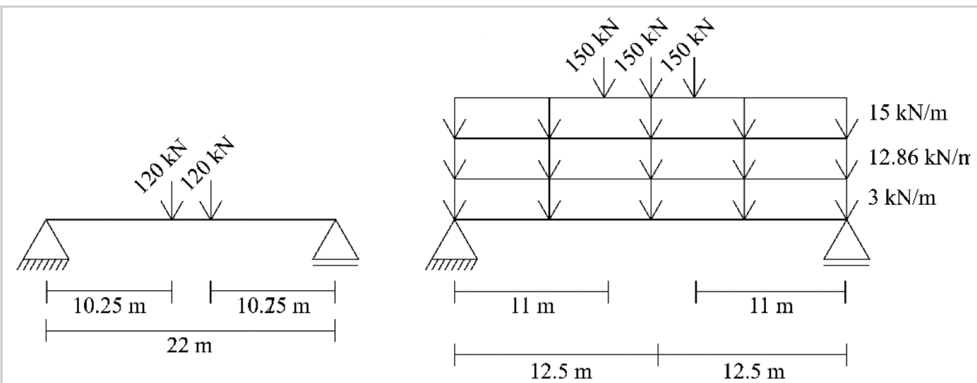

Figure 2 – Beam models of (a) Abbas *et al.* (2018) and (b) Ferreira (2007).

The authors point out that the self-weight was considered by the program. Therefore, the lower and upper limits assigned to the GA are stated in Table 3. The initial population contains 120 individuals and the following, 60. The rate of elite individuals and crossing of the intermediate type are 0.05 and 0.8, respectively, whereas the mutation rate is random. The GA is performed primarily with an entirely random initial population, thereby obtaining an optimal local response.

Table 3 – GA variables: lower and upper limits.

Variable	Lower limit	Upper limit
t_{fs} and t_{fi} [cm]	1.6	4.44
b_{fs} and b_{fi} [cm]	10	55
d [cm]	55	200
n_t [units]	0	20

3.1 Example 1 – Prestressed Monosymmetric I-shaped Steel Beam (Abbas *et al.*, 2018)

Abbas *et al.* (2018) studied a Finite Element model via the ANSYS optimization package. Two objective functions were employed to minimize the strain energy and the material weight of two steel girders – with and without prestressing. Moreover, straight-line tendons were considered by the structural model.

The aforementioned researchers did not delimit the prestressing losses. Thus, it was convenient to vary it by 0, 5, 10, 15, and 20% to obtain different parameters of comparison. Therefore, the input data considered: 2-point loads of 120 kN applied at 10.25 and 11.75 m from the left support; *L* of 22 m; t_w of 10.40 mm; tendons of 9.5 mm allocated

50 mm above the inferior flange bottom; f_y of 200 MPa; and E of 200000 MPa.

The optimum results are displayed on Table 4 and its constraints are graphically represented on Figure 3. The nomenclature adopted by this example indicates the type of the beam (MS or DS) as well the related losses (*L*), i.e., 0, 5, 10, 15, or 20.

Table 4 – Doubly-symmetric (DS) and monosymmetric (MS) results based on Abbas *et al.* (2018).

Example	d (mm)	b_{fi} (mm)	b_{fs} (mm)	t_{fi} (mm)	t_{fs} (mm)	t_w (mm)	$N_{tendons}$	Ix(e+4mm^4)	δ (mm)	σ_c (MPa)	σ_t (MPa)	Total Cost (R$)
Abbas et al. (2018)	984.3	390.8	391.8	20.80	22.60	10.40	3	465231.00	56.83	-193.40	147.20	60240.10
MS0	1200	250	300	16.00	16.01	10.40	7	445518.29	38.68	-196.44	169.20	48291.32
MS5	1160	290	210	16.00	25.24	10.40	5	443415.54	46.24	-199.95	184.46	49198.32
MS10	1320	160	330	16.00	16.06	10.40	7	504286.07	32.51	-162.01	186.57	48970.94
MS15	1140	290	170	16.00	32.28	10.40	7	427262.86	44.74	-200.00	179.67	49475.77
MS20	1200	260	300	16.00	16.16	10.40	7	452928.76	42.21	-198.00	178.50	48745.42
DS0	1080	270	270	20.80	20.80	10.40	5	412110.28	56.86	-194.06	159.60	50226.59
DS5	1080	270	270	20.80	20.80	10.40	5	412110.28	57.54	-195.28	162.55	50226.59
DS10	1080	270	270	20.80	20.80	10.40	5	412110.28	58.22	-196.50	165.49	50226.59
DS15	1080	270	270	20.80	20.80	10.40	6	412110.28	56.60	-193.62	158.47	50470.70
DS20	1080	270	270	20.80	20.80	10.40	6	412110.28	57.42	-195.08	162.00	50470.70

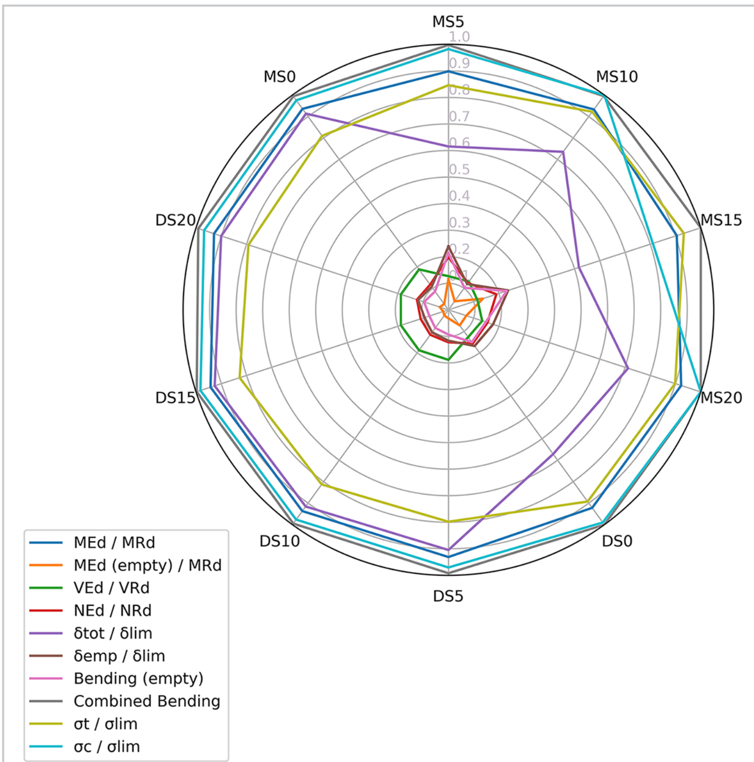

Figure 3 – Constraint results for Example 1.

The MS geometries varies with prestressing losses. On the other hand, the DS shapes has presented exactly the same geometry. Thus, as expected, the MS are more able than DS to change their shapes without exceeding the constraints. Naturally, the inertia on the DS is constant.

Due to the impossibility of reduction on the DS geometries without exceeding the security limits, GA decreases the number of tendons. Moreover, the higher (?) on the tendons and inertia led to lower displacements. Therefore, the MS showed greater values than DS about the tensile and compressive strength.

Besides this study presents a greater number of tendons compared to Abbas *et al.* (2018), the total structural costs were lower than the reference for each case. The large flanges and thicknesses, as well as the smaller depth of cross-section, was not the best combination, increasing the final cost.

Figure 4 illustrates the total structural cost normalized according to Abbas *et al.* (2018). In general, each of the models are better choices than the reference. The greatest reduction was found on the MS0 with 20.00%. On the other hand, other models are not unsatisfactory options, considering those costs near to MS0. The large deviation is 4.00% (DS15 and DS20), which is negligible in the authors point of view. The designer will choose a model based on the local parameters of construction, e.g., architectonic project or structural constraints.

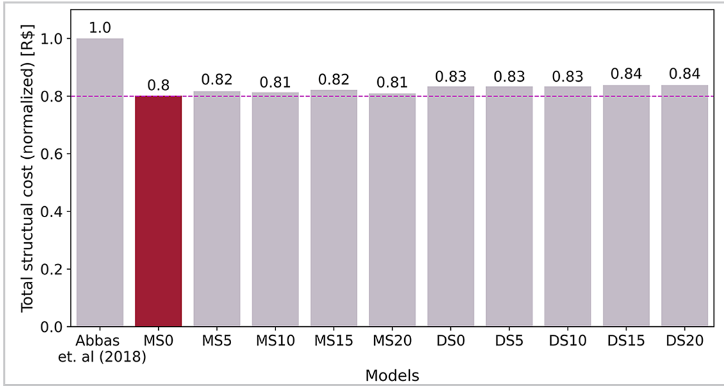

Figure 4 – Total structural cost for Example 1.

3.2 Example 2 – Prestressed Monosymmetric I-shaped Steel Beam (Ferreira, 2007)

Ferreira (2007) analyzed prestressed I-shaped beams (i) with polygonal and (ii) straight-line tendons. However, this study focused only on (ii).

The tw varied at 12.5 and 16.0 mm – lower values exceeded the GA constraints. Moreover, bfs ranged as follows: 22.4, 25.0, 31.5, 37.5, and 44.4 mm. Therefore, the input data considered: 3-point loads of 150 kN applied at 11, 12.5, and 14 meters from the left support; overload of 3 kN/m; permanent load of 12.86 kN/m; serviceability overload of 15 kN/m; L of 25 m; tendons of 15.2 mm allocated 100 mm below the inferior flange bottom; fy equal to 345 MPa; E of 205000 MPa; and prestressing losses of 12.3%.

The optimum results are displayed in Table 5 and their constraints are graphically represented on Figure 5. Different from example 1, the nomenclature herein indicates only the type of the beam (MS or DS) and an identification number.

Table 5 – Doubly-symmetric (DS) and monosymmetric (MS) results based on Ferreira (2007).

Example	d (mm)	b_{fi} (mm)	b_{fs} (mm)	t_{fi} (mm)	t_{fs} (mm)	t_w (mm)	$N_{tendons}$	Ix(e+4mm^4)	δ (mm)	σ_c (MPa)	σ_t (MPa)	Total Cost (R$)
Ferreira (2007)	1000	380	500	32.00	44.40	16.00	18	853611.00	58.11	-169.84	328.18	134317.52
MS01	1630	410	190	16.00	39.82	16.00	10	1425607.95	55.20	-344.96	271.90	104810.90
MS02	1620	410	180	16.00	44.40	16.00	9	1423223.71	59.51	-343.50	288.69	104755.85
MS03	1640	550	230	16.00	39.82	12.50	8	1581053.44	57.71	-331.97	260.59	99801.48
MS04	1680	530	200	16.00	44.40	12.50	8	1623991.92	55.56	-330.14	257.95	99407.54
MS05	1620	410	210	16.00	37.50	16.00	9	1426673.17	59.34	-342.80	287.76	104739.17
MS06	1640	540	240	16.00	37.50	12.50	9	1563784.41	54.45	-331.21	250.88	99613.63
MS07	1610	420	250	16.00	31.50	16.00	9	1425142.96	59.65	-342.41	286.06	104981.83
MS08	1660	530	280	16.00	31.50	12.50	9	1594697.76	52.95	-327.36	248.46	99575.71
MS09	1630	410	300	16.00	25.00	16.00	9	1444331.46	58.50	-342.90	283.31	104701.26
MS10	1660	530	350	16.00	25.00	12.50	9	1599878.18	52.74	-326.19	247.61	99604.15
MS11	1610	420	340	16.00	22.40	16.00	9	1423455.23	59.78	-344.34	285.02	104695.19
MS12	1670	540	390	16.00	22.40	12.50	8	1636304.76	55.25	-326.73	254.04	99827.13
DS01	1210	310	310	39.82	39.82	16.00	18	1038055.18	69.61		108.77	118056.96
DS02	1170	300	300	44.40	44.40	16.00	19	1012765.33	69.49	-248.03	98.74	121553.88
DS03	1260	320	320	39.82	39.82	12.50	16	1120211.86	69.95	-257.31	120.02	110545.52
DS04	1190	310	310	44.40	44.40	12.50	18	1042745.55	70.17	-251.09	100.59	114313.04
DS05	1240	310	310	37.50	37.50	16.00	17	1051585.88	71.34	-262.31	122.19	115270.03
DS06	1290	330	330	37.50	37.50	12.50	15	1157792.70	70.48	-260.81	131.13	109230.62
DS07	1320	330	330	31.50	31.50	16.00	15	1127893.83	71.20	-270.58	143.96	111668.59
DS08	1390	350	350	31.50	31.50	12.50	13	1260938.21	68.85	-267.51	151.34	104840.53
DS09	1400	360	360	25.00	25.00	16.00	14	1178925.00	68.99	-276.61	154.55	107825.48
DS10	1520	390	390	25.00	25.00	12.50	10	1420564.06	68.98	-278.78	187.63	101257.04
DS11	1470	370	370	22.40	22.40	16.00	12	1254444.70	70.95	-287.36	182.15	106163.28
DS12	1580	410	410	22.40	22.40	12.50	9	1491047.92	68.26	-282.45	199.72	99903.72

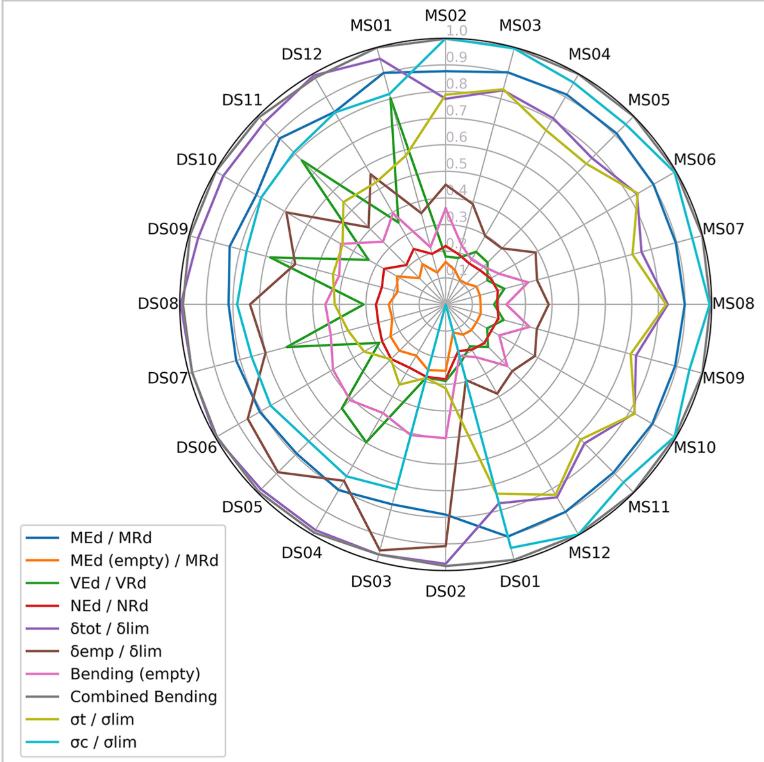

Figure 5 - Constraint results for Example 2.

The MS shapes obtained higher d than DS, according to the conclusion in Example 1 about the MS capacity of its shape changing. Furthermore, the inertia clearly increased, meaning unnecessary higher number of tendons. Thus, MS shapes support more elevated tensile and compressive strength than DS.

Unlike Example 1, the number of tendons was lower than the referenced. In general, MS got a half of Ferreira's (2007) values. This fact jointly with the smaller geometry, increases the total structural cost of Ferreira (2007).

Figure 6 illustrates the total structural cost normalized according to Ferreira (2007).

As such, the MS as well as DS models, obtained better results than the reference. Considering the design method, i.e., traditional technique, employed by the aforementioned author, lower costs were also expected. The best result was MS04 with 25.70% of reduction. However, MS03, MS06, MS08, MS10, MS12, DS10, and DS12, resulted almost the same value as MS04. Between those models, the large deviation is 0.0138%, again negligible in the authors point of view. Therefore, any of these models can be designed with a lower cost, considering the applicability will need to consider the local conditions.

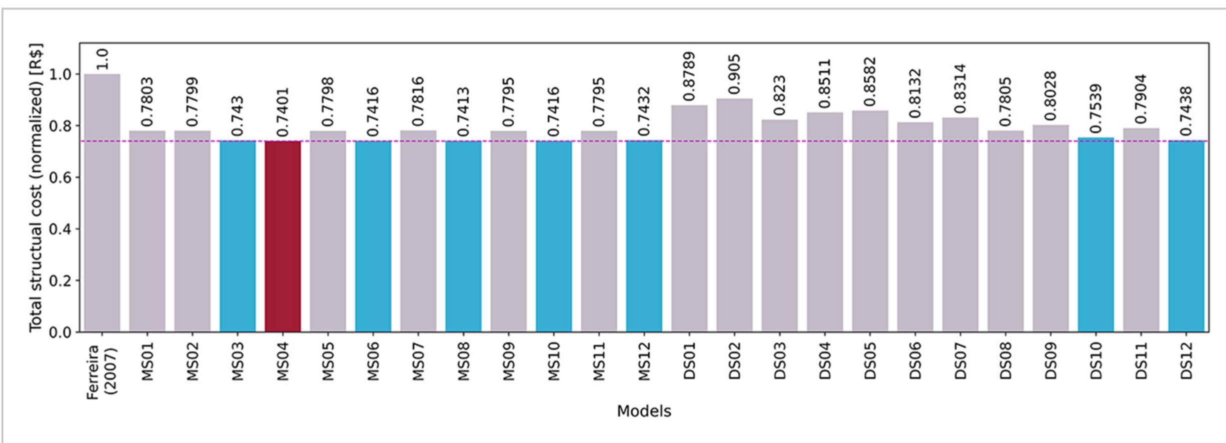

Figure 6 - Total structural cost for Example 2.

The influence of b_{fs} and t_w on the total structural cost are demonstrated by Figure 7. Overall, the MS models results optimum values than DS. Furthermore, the DS bfs are proportional to the cost, different from MS. Moreover, as well as the bfs decrease, DS costs have a tendency to show almost MS costs – about the same t_w.

Therefore, DS models with t_w equal to 12.5 mm and b_{fs} less than or equal to 31.50 mm, results minor total structural costs than MS models with t_w equal to 16.0 mm. In this respect, for small values of b_{fs}, the MS are almost equal DS geometries.

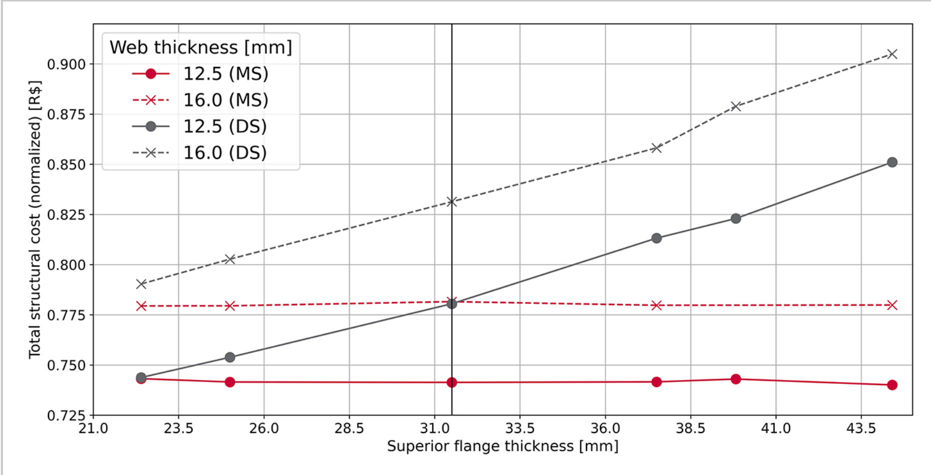

Figure 7 – Superior flange thicknesses influences.

4. Conclusions

This article presents an optimum design for prestressed I-shaped steel beams via MATLAB's native GA technique. Savings in material weight as well as prestressing tendons anchorage is the objective function – total structural cost. Abbas *et al.* (2018) and Ferreira (2007) were the examples to validate and evaluate the algorithm. Furthermore, significant models were proposed considering the objective function without exceeding the security limits. The design method followed the Brazilian standard NBR 8800:2008. Thus, the main conclusions from the study are:

- Example 1 (Abbas *et al.*, 2018) resulted in 20.00% of reduction considering 0% of prestressing losses (MS0). However, the largest deviation from MS0 is 4%. Thus, the MS as well as DS models are able to be applied.
- Example 2 (Ferreira, 2007) reduced the total structural cost by 25.70% (MS04). MS03, MS06, MS08, MS10, MS12, DS10, and DS12 are also alternatives to MS04. The largest deviation is 0.0138%. Therefore, for small values of bfs, the model shapes tend to be a DS.

In general, monosymmetric was the better option compared to the doubly-symmetric shapes. Nevertheless, the deviation between some shapes could be neglected. For that reason, the proposed formulation was efficient to obtain the optimal solution for the prestressed I-shaped steel beams. Moreover, the GA proved to be useful with a low computational cost.

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