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OPTIMAL DESIGN OF BEAM-COLUMN CONNECTIONS OF PLANE STEEL FRAMES USING THE COMPONENT METHOD

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ABSTRACT

This paper presents a methodology for optimization of beam-column connections of plane steel frames. The objective is to obtain beam-column connections mechanically more efficient and with minimum cost by determination of the optimal dimensions the components of the connection; Satisfying mechanical constraints associated with the bending moment and the rotational stiffness of the connection, however, without compromising its safety and integrity. Minimum and maximum limits of geometric parameters are considered, according to current regulations. Computational codes were developed to calculate the bending moment and the rotational stiffness of the connection using the "Method of Components" of Eurocode 3. Initially, it was developed a digital database with structural profiles, steel plates and commercial bolts obtained from catalogs of manufacturers, with automatic access of the data by the computational modules of structural analysis and optimization. In the optimization model, is adopted the connection with extended end plate without stiffeners, the design variables are the dimensions and the thickness of the end plate, the diameter and the location of the bolts. In the optimization process, in the search for global minimum of the problem we use genetic algorithms with continuous and discrete variables, with the discrete variables being associated to the database. In this way, this paper presents a computational tool developed integrally in MATLAB® environment for analysis and optimal design of beam-column connections for plane steel frames. Are present applications that show quite satisfactory results when compared with results available in the literature.

Keywords: Structural optimization, Steel beam-column connections, Bolted end-plate connections.

1 INTRODUCTION

In recent years, there has been a great growth of industrial buildings and residences structured in steel. The steel structures are formed by the connection of several structural elements aiming the efficient conduction of the external forces acting on the structures for the foundations. The steel has

advantageous physical and mechanical characteristics for use in the construction of plane frames, such as: good relationship between strength and structural weight, adaptability to various architectural forms, wide variety of profiles available in the market, great control in the manufacturing process in the mills which results in greater reliability in the use of these buildings.

In plane steel frames, usually the connections between the structural elements are the most critical sectors of the structure, where several internal requests occur, generating probable foci of structural insecurity. Therefore, it is indispensable that the connections are able to adequately transmit the efforts between the elements.

In conventional analysis, the beam-column connections of steel frames have been simplified by considering them to be flexible or rigid connections. Flexible connections are those in which their rotational stiffness is ideally zero, that is, the relative rotation at the end of the beam is free; the rigid connections are those in which their rotational stiffness is considered infinite, that is, there is not rotation between the connected elements. However, this consideration is an idealized form that does not reflect the real behavior of the connections. However, real connections always have a certain degree of rotational stiffness and flexural resistance that generate an intermediate behavior between the two theoretical extremes mentioned, called semi-rigid connections [1].

The simplification of the behavior of beam-column connections is still a frequent design practice, since local design standards only require verification of the flexural strength of the beams and columns in connection with the requesting stresses of the connection and do not contemplate the mechanical behavior of the connection (calculation of ultimate flexural resistance, rotational stiffness and degree of rotation) [2]

The process of structural analysis of a connection can be represented by a rotational spring that connects the midline of the members, considering three basic properties: resistant moment ($M_{j,Rd}$), rotational stiffness (S_j) and rotational capacity (Φ_{cd}), according to Figure 1.

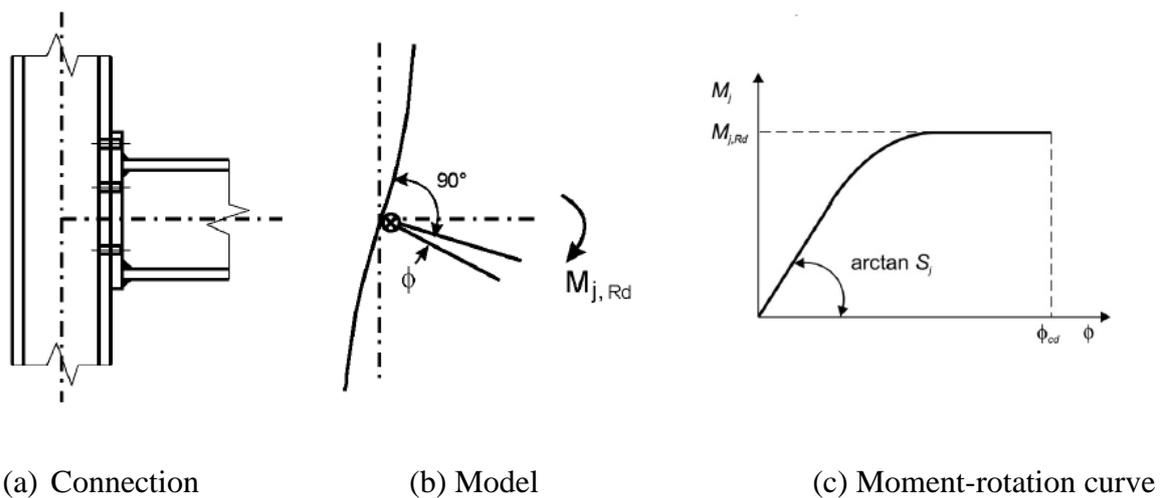| (a) Connection | (b) Model | (c) Moment-rotation curve |

Figure 1: Moment-rotation curve for a connection.

The characterization of the moment-rotation curve of a connection is based on the evaluation of its properties of flexural resistance, rotational stiffness and rotational capacity (ductility). The

Figure 1 shows the moment-rotation curve of a beam-column connection as a function of the applied moment and relative rotation produced by this moment.

In this paper the connection with extended end plate (Figure 2) will be studied, because it has wide use in plane steel frames. Besides that, this type of connection presents a semi-rigid behavior, according to the components used and principally without stiffeners.
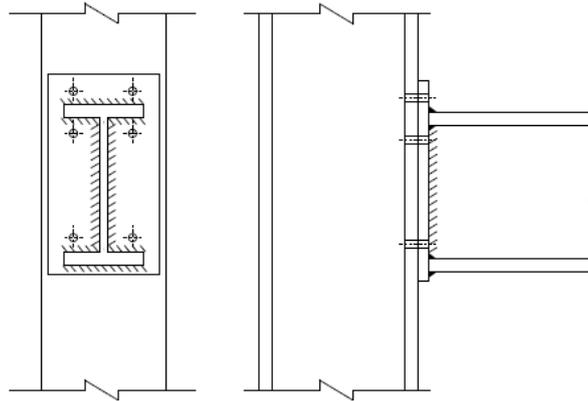

Figure 2: Extend end-plate connection [3].

In recent years, numerous strategies have been developed to minimize the cost of manufacturing steel frame with semi-rigid connections, notably aiming to minimize the weight of structural profiles. In general, only the dimensions of the profiles are considered design variables, while the components of the connections are not considered, in this way, it is observed that these models do not guarantee that the resulting structure is really the optimal solution.

The specific characteristics of each problem are those that determine the most appropriate numerical method to be used. Currently there are several optimization algorithms that are based on the observation of nature's phenomena. Genetic Algorithms (GAs) are evolutionary heuristics of optimization based on the natural evolution of the species. These algorithms are procedures of search of global extreme values that has as strategy to find the individual that best adapts to the model of optimal project adopted to represent a certain problem. In structural optimization, in recent years, many researchers have used GAs to solve a great variety of problems.

One of the frequently objectives used in structural optimization is the weight or volume minimization of the structure. In steel frames, it is observed that the connections between the elements, especially the beam-column connections represents only a small part of the total weight of the structure, however, such connections may have a significant manufacturing cost, because it is composed of several parts with different manufacturing procedures often with specific finishing details. Previous studies have shown that the manufacturing cost of the connections depends directly on the degree of rotational stiffness of the connection [4]. Thus, this study considers the real cost of the connections to each configuration defined during the optimization process.

Thus, a methodology for the optimization of beam-column connections with extended end plates is presented. It seeks to determine the optimum dimensions for thickness of the end plate, the diameter and the location of the bolts, according to the profiles of plates and bolts available in the market are intended. In this way, the computational tool presented consists of two computational modules, the analysis and optimization modules that communicate with each other automatically

3

through computational interfaces. Computational codes were developed in the MATLAB® computing environment.

Because of the absence of local specifications for the calculation of semi-rigid connections in the Brazilian steel constructions standard, NBR 8800: 2008 [5], in the present work we opted for the Components Method of Eurocode 3, because the great acceptance of this technique by technicians and scientists. The computational codes for the analysis of the mechanical behavior of the connection were implemented based in the program Calc_US_MC [6], coded according to Eurocode Annex J. These codes were updated according to Eurocode 3 - part 1-8 [7] by the authors of this work.

A database of structural profiles obtained from manufacturers' catalogs was also implemented, which is automatically accessed by the computational modules of structural analysis and optimization algorithm.

In the computational optimization module, the genetic algorithm provided in the MATLAB® optimization toolbox was used.

2 COMPONENTS METHOD

The components method is a mechanical-analytical method that allows to characterize the mechanical behavior of the connections. It consists of dividing the connection in a series of springs, in which each one has its own resistance and stiffness the tension, the compression and the shear. Thus, to apply the components method is necessary adequately characterize the mechanical behavior of each component. The total resistance of the connection is obtained from the resistances of its components. The total resistance is conditioned to the resistance of the weakest link, analogy to the behavior of a current.

The Eurocode 3 part 1-8 [7] considers 20 basic components for designing connections on steel frames. In Figure 3, it is possible to identify the components of the extended end-plate connection, separated by components in traction zone, compressed zone or flexed zone.
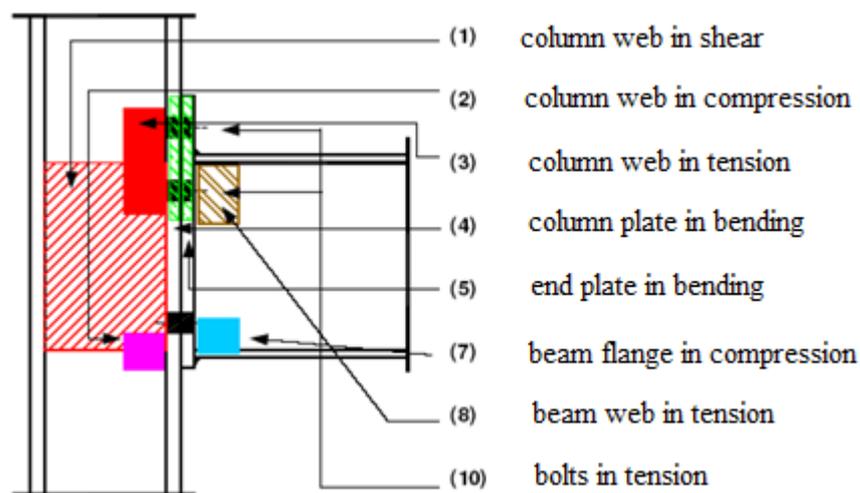

Figure 3: Components of the extended end-plate connection [1].

In beam-column connections with extended end-plate, the bending moment resistance is determined by Eq. (1):

$$M_{j,Rd} = \sum_r h_r F_{tr.Rd} \tag{1}$$

where r identifies the bolt lines of the traction zone, $F_{tr.Rd}$ is the tension resistant of the bolt line r e h_r is the distance between bolts line r and the adopted center of compression, as in Figure 4 .
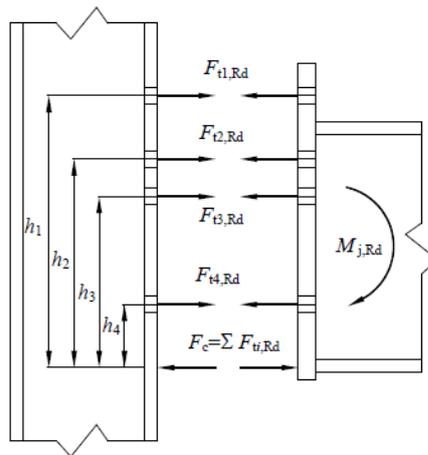

Figure 4: Distribution of forces on the bolts [3].

While the rotational stiffness of a connection is obtained from the combination of stiffness values of the components, initially associated in series and later in parallel, as shown in Figure 5 and defined by Eq. (2).
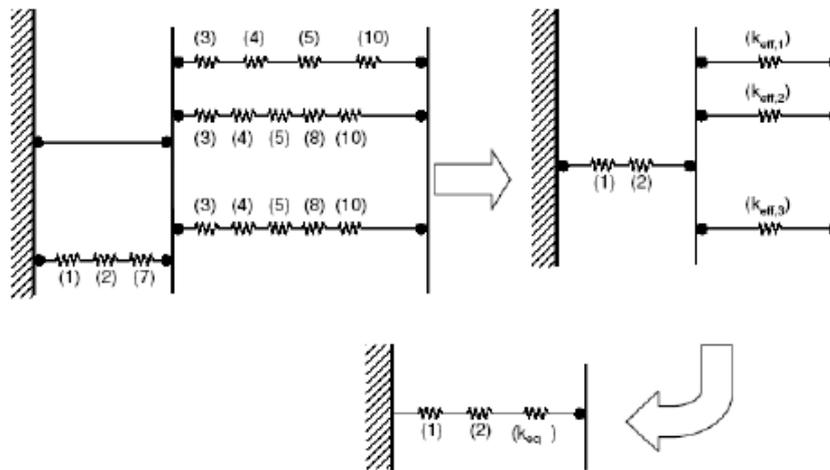

Figure 5: Sequence of calculation of the rotational stiffness of a connection [2].

$$S_j = \frac{Ez^2}{\mu\left(\dfrac{1}{k_1} + \dfrac{1}{k_2} + \dfrac{1}{k_{eq}}\right)} \tag{2}$$

where E is the Elastic Modulus of steel, k_1 and k_2 are the stiffness values calculated for components 1 and 2, z is the equivalent lever arm (up to the center of compression), k_{eq} is the equivalent stiffness of the components, and μ is the ratio between initial and secant stiffness.

3 GENETIC ALGORITHM

Genetic algorithms (GAs) are search algorithms based on the natural process with the idea that those living beings that best adapt would tend to survive. These algorithms are classified as evolutionary algorithms. Genetic algorithms are widely used to solve problems, in which, in a set of elements, it wants to find that or those that best meet as imposed conditions.

The genetic algorithms were initially developed by John Holland in 1965 through a research that initially aimed to study the evolutionary processes, so that the phenomena of adaptation and evolution of the real world were simulated through computational processes [8].

Genetic algorithms work with principles evolutionary and genetics theories that can be modeled through computational codes. In general, GAs are flexible and efficient strategies for in complex spaces, such as the solution space for optimization [9].

The algorithm begins by arbitrarily defining a population of individuals represented by an analogy with the chromosomes, which represent a set of solution candidates to the problem. The evaluation of the fitness of the individuals of this population is used to generate a new population with characteristics better than those of the previous population. That is, all solution candidates defined in each generation are analyzed to define a numerical quantification in relation to the objective function and the design constraints, that is, to verify their suitability. According to the suitability of the candidates, operators of reproduction, crossover and mutation are applied to define a new population. This procedure is repeated until it reaches thee stop criteria.

4 FORMULATION OF THE PROBLEM

This work aims to develop a methodology to minimize the cost of fabrication of beam-column connections without compromising the mechanical efficiency of the structure, considering the semi-rigid behavior of the connections and using the Components Method of Eurocode 3 [7].

Seven design variables were adopted: the diameter of the bolts (d); the thickness of the end-plate (t_p); the width of the end-plate (b_p); the horizontal distance between the axis of the bolts and the edge of the plate (e); the vertical distance between the first row of the bolts and the edge of the plate (e_x); the vertical distance between the bolts axes of the first and second row of the bolts (p_x); and the vertical distance between the second and third row bolts (p). Since the diameter of the bolts and the thickness of the plate are discrete variables, they are obtained in automated form from a digital database of profiles, plates and bolts with commercial templates.
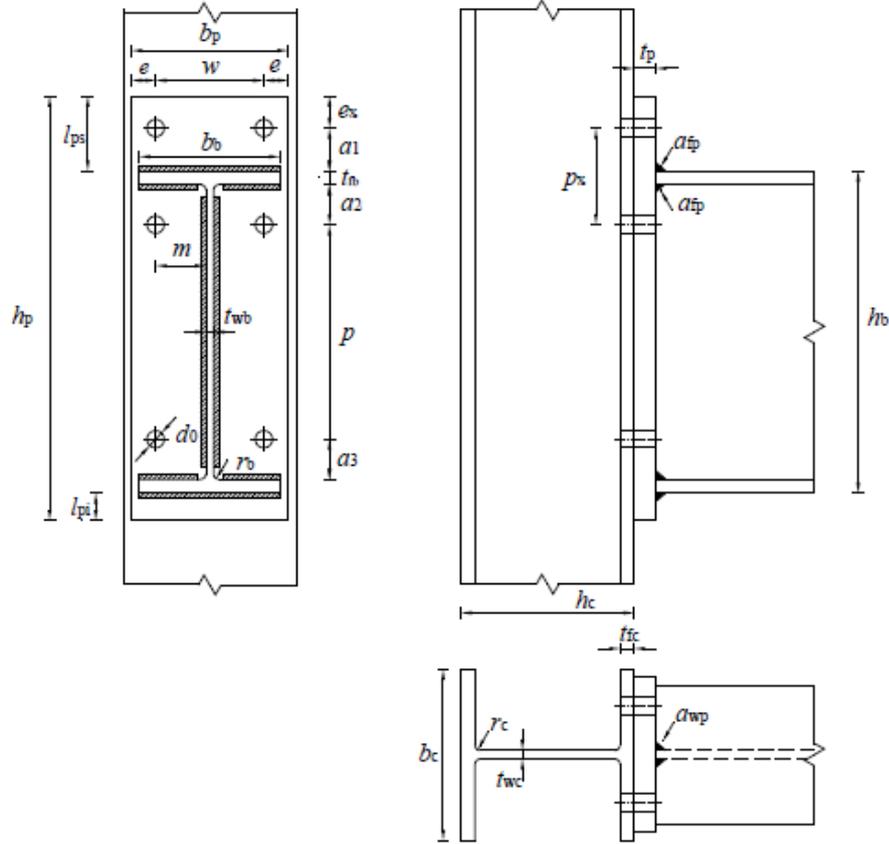
Figure 6: Geometric parameters of extended end-plate connection [3].

The objective function used in this work considers the total cost of beam-column connections. The total cost comprises the cost of the materials, the cost of labor and the equipment used; it is observed that each component of the connection has a cost different from the other, Eq. (3). This formulation was proposed by Pavlovčič et al. [10] and it was also used by Díaz [11].

$$C_{US} = C_b + C_{c,t} + C_{c,opm} + C_h + C_p + C_s + C_{w,mf} + C_{w,mc} \qquad (3)$$

where, C_b is the material cost for the bolt assembly (bolt, nut and two washers), $C_{c,t}$ is the cost associated with the time taken to cut the end-plate, $C_{c,opm}$ is the cost of the oxygen–propane mixture used for cutting the end-plate, C_h is the hole forming cost, C_p is the cost of painting the end-plate, C_s is the cost of the steel for end-plate, $C_{w,mf}$ is the manufacturing cost for welding the end-plate (including all associated time), and $C_{w,mc}$ is the cost of the welding material consumables (electrodes, wire, etc.).

The design constraints considered in this work aim to control the minimum allowable values for the bending moment and the rotational stiffness of the connection, according to Eq. (4) and Eq. (5).

$$\frac{M_{j,Ed}}{M_{j,Rd}} - 1 \leq 0 \tag{4}$$

$$\frac{S_{j,min}}{S_j} - 1 \leq 0 \tag{5}$$

where $M_{j,Ed}$ is the requesting moment obtained from the optimized steel frame and $S_{j,min}$ is the minimum allowable rotational stiffness value obtained from the optimized steel frame.

In addition, geometric constraints were also considered, to verify the lower and higher limits of the design variables, (l_b) and (l_b), according to recommendations of Eurocode 3 [7] (Table 1).

Table 1 Lower and upper limits

Parameter	Minimum Value (mm)	Maximum Value (mm)
b_p	Beam width	Column width
e	$1,2d_0$	30
e_x	$1,2d_0$	30
p_x	$2,2d_0$	$min[200; 14(\min(t_p, t_{fc}))]$
p	$2,2d_0$	$min[200; 14(\min(t_p, t_{fc}))]$
w	$2,4d_0$	$min[200; 14(\min(t_p, t_{fc}))]$
a_1	y	-
a_2	y	-
a_3	y	-

The values of the holes diameters (Eq. (6)) of the bolts (in mm) are:

$$
\begin{aligned}
d_0 &= d + 1, \text{ se } d \leq 12 \\
d_0 &= d + 2, \text{ se } 12 < d \leq 12 \\
d_0 &= d + 3, \text{ se } d > 12
\end{aligned}
\tag{6}
$$

The minimum distance between the bolts and the beam flange, for that the bolts can be removed without difficulty, is related to the bolt diameter as shown in Eq. (7).

$$
\begin{aligned}
y &= 30 \quad se \quad d \leq 20 \\
y &= 35 \quad se \quad 20 < d \leq 22 \\
y &= 40 \quad se \quad d > 22
\end{aligned}
\tag{7}
$$

To use the GA of the MATLAB® optimization toolbox, the constrained optimization problem needs to be transformed into an unrestricted problem, a single equation that considers the simultaneous effect of the objective function and the constraints. For this transformation a penalty function was used, based on the level of violation of the constraints. In this case, the "ga", algorithm of MATLAB®, uses the Lagrangean Augmented method to transform the problem with constraints into an unrestricted problem.

The Augmented Lagrangean Method consists of the combination of the objective function and the nonlinear constraint function, the penalty parameters λ_i and the slack variables s, as shown in Eq. 8:

$$L(x, \lambda, s, \rho) = f(x) - \sum_{i=1}^{m} \lambda_i s_i \log(s_i - c_i(x)) + \sum_{i=m+1}^{mt} \lambda_i ceq_i(x) + \frac{\rho}{2} \sum_{i=m+1}^{mt} ceq_i(x)^2 \quad (8)$$

where the parameters λ_i are known as Lagrange multipliers and are non-negative. The slack parameters s_i convert the inequality constraints into equalities constraints and are non-negative, ρ is the one positive penalty parameter.

In this way, the algorithm minimizes a sequence of sub problems, each of which approximates the original problem. Each sub problem has a fixed value of λ, s, and ρ. When the sub problem is minimized to a required precision condition and satisfies as feasibility conditions, the Lagrangean estimates are updated. Otherwise, the penalty parameter (ρ) is increased. These steps are repeated iteratively until the stop criteria are satisfied.

For the examples, which will be presented below, used a population with 24 individuals, with 2 guaranteed to survive for the next generation. In addition to the crossover operator with probability of 0.8.

5 APPLICATIONS

For validation of the computational tool developed in this work, an application using data available in the literature is presented below. Previously a database was implemented containing geometric properties of commercial profiles, commercial plates and bolts available in manufacturers' catalogs. Access to the database through the analysis and optimization modules is done automatically.

The application considers a plane steel frame of 3 bay and 2 story. Thus, the frame has 4 different connections, according to Figure 7. Previously, in 2005, this frame was studied by Cabrero and Bayo [12] and were obtained optimal profiles of beams, columns and minimal values of rotational stiffness and flexural resistance of the connection, as indicated in Table 2. However, this work did not include the optimization of beam-column connections and, in 2012, another results for A and C connections were presented by Diaz [11],

The properties of the materials for these connections are: steel S275, with yield stress $\sigma_y = 275$ MPa and ultimate stress $\sigma_u = 430$ MPa; Elastic Modulus E = 210 GPa; Poisson's ratio υ = 0.3; mass density ρ = 7820 kg / m³; Steel bolts grade 8.8, with yield stress $\sigma_y = 640$ MPa and ultimate stress $\sigma_u = 800$ MPa. For the purposes of comparison, the materials and profiles used in the reference work were maintained [12].
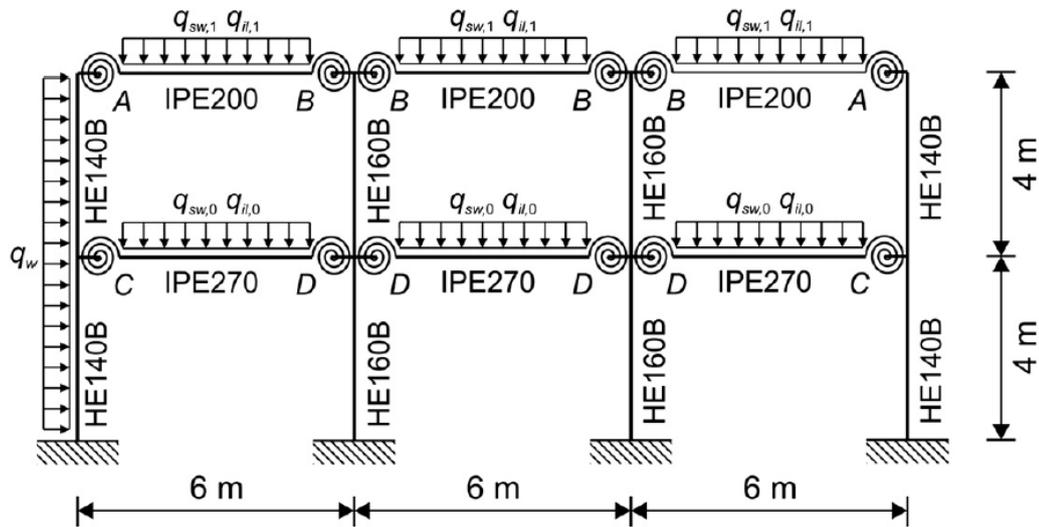
Figure 7: Dimensions and loads for the steel semi-rigid frame optimized in [12], the applied loads in kN/m are: wind q_w=3.80; self-weights $q_{sw,0}$=7.80 and $q_{sw,1}$=6.50; applied $q_{il,0}$=11.20 and $q_{il,1}$=3.20.

The Table 2 shows the optimum profiles of beams, columns and the values of the applicant bending moments and the minimum rotational stiffness for frame connections, obtained by Cabrero and Bayo [12] for this frame.

Table 2 Optimal beams and columns sizes and the stiffness and resistance values for connection [12].

Connection	Beam	Column	$S_{j,min}$(kNm/rad)	$M_{j,Ed}$(kNm)
A	IPE200	HE140B	9000	22
B	IPE200	HE160B	9000	35
C	IPE270	HE140B	16000	40
D	IPE270	HE160B	16000	60

From the optimum configuration shown in Table 2, the optimization of A, B, C and D connections of the frame was performed. The Figures 8 to 11 show the history of the iterations to obtain the minimum cost for each frame connection. The graphs show the relationship between the best individual and the average of each generation. All restrictions were met, within the established tolerance. The points outside the iteration curve reflect all the processing of the genetic operators in the formation of the new population of individuals. This type of behavior, very common in GAs, because the GAs have a probabilistic nature.
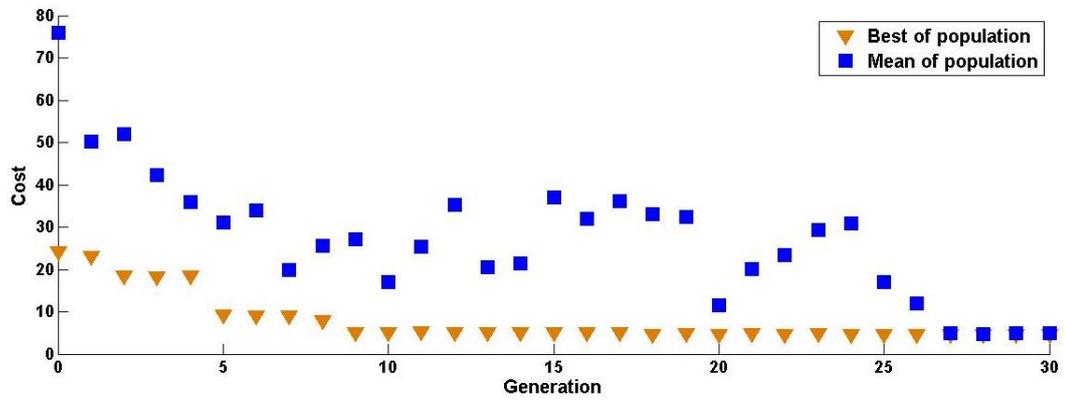
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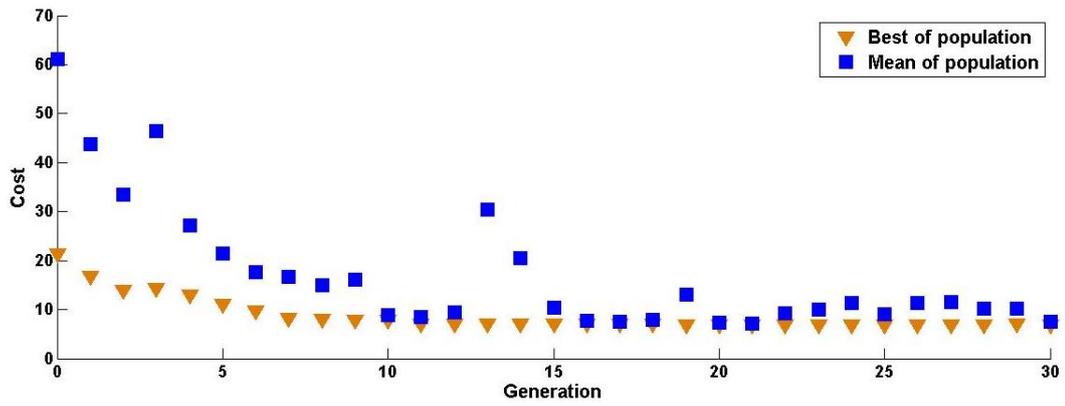Figure 8: Graph of iteration of connection A.

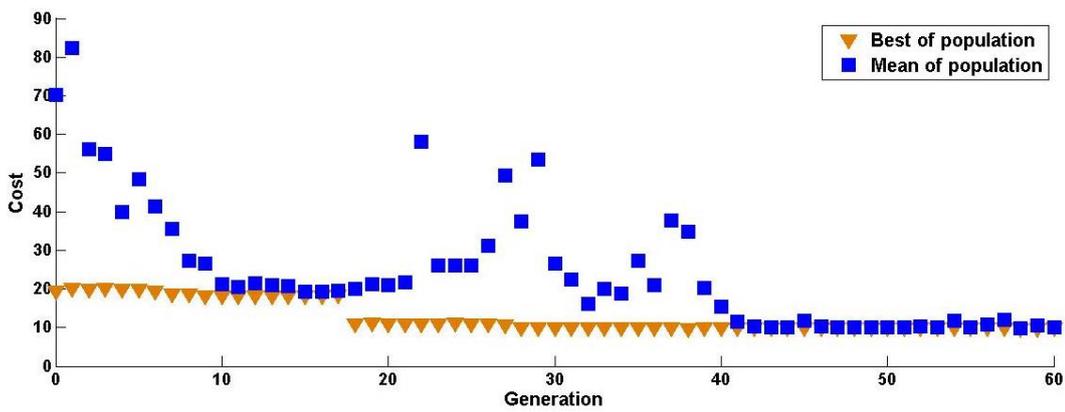Figure 9: Graph of iteration of connection B.

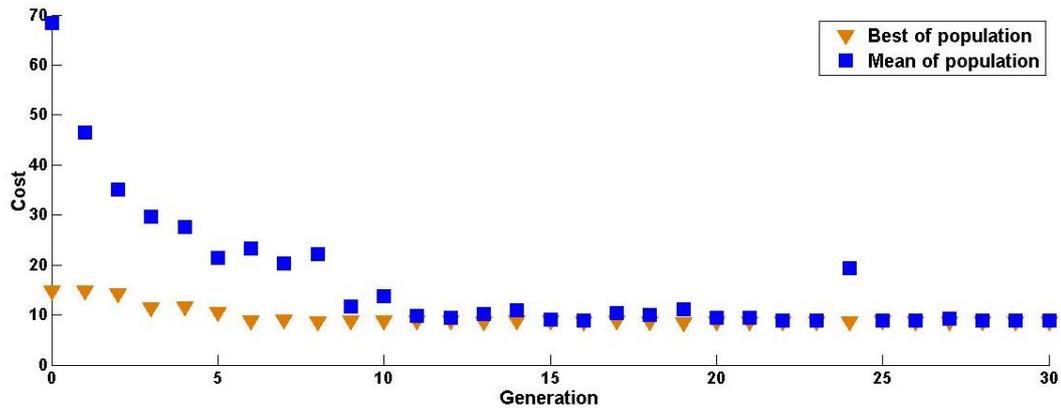Figure 10: Graph of iteration of connection C.

11

Figure 11: Graph of iteration of connection D.

Table 3 shows the configurations of the connections obtained in this study, the configurations of the optimized connection presented by Cabrero and Bayo [12] and the configurations of the connections A and C obtained by Diaz [11].

Table 3 Optimum design variables.

Parameter	Cabrero and Bayo				Diaz		AG (This study)			
(mm)	A	B	C	D	A	C	A	B	C	D
d	20	16	22	22	16	16	12	16	16	16
b_p	140	140	140	140	115	136	101.2	100	135	135
h_p	285	295	345	345	-	-	263	266.2	358.5	334.4
t_p	10	12	15	14	12	11	16	9.5	19	12.5
p_x	90	110	70	70	61	61	69.5	82.5	89.3	87.2
w	80	80	80	80	-	-	45	51.5	75.2	76.5

Table 4 presents the cost (in Euros), the resistant moments and rotational stiffness obtained by Cabrero and Bayo [12], Diaz [11] and by this study. To calculate the cost of the connections presented by Cabrero and Bayo [12], was used the Eq. (3) and to obtain the stiffness and the resistant moments was used the analysis module of this computational tool. The results presented in Table 4 are used to compare and validate the results obtained in this work.

Table 4 Cost, resistant moment and rotational stiffness.

Connection	Cabrero and Bayo			Diaz			AG (This study)		
	Cost €	$M_{j,Rd}$ (kNm)	S_j (kNm /rad)	Cost €	$M_{j,Rd}$ (kNm)	S_j (kNm /rad)	Cost €	$M_{j,Rd}$ (kNm)	S_j (kNm /rad)
A	21.19	41.23	8042.50	12.39	41.28	9437.90	4.76	34.30	9076.00
B	12.09	38.60	12996.00	-	-	-	7.00	35.10	16341.00
C	30.00	55.88	17058.70	13.50	54.29	16040.90	10.10	51.60	16107.00
D	29.80	102.20	47418.00	-	-	-	8.78	73.00	41667.00

It is observed that the computational tool presented here obtained good results in comparison with other studies available in the literature. Comparing the costs, this work obtained a reduction of 67% in relation to the results presented by Cabrero and Bayo. In relation to the connections A and C presented by Diaz [11] the computational tool obtained a reduction of 42%.This high reduction is related to the database, because Diaz [11] used bolts with diameters starting 16 mm and this work used a larger database with bolts starting from 12 mm, which gives to AG more choice.

The present computational tool was able to increase the efficiency of the connections, so that the values of the resistant moments and the rotational stiffness approximated more than the minimum admissible value, but without violating the restrictions.

6 CONCLUSION

This paper presents a numerical model and a computational tool for the optimal design of beam-column connections for plane steel frame using genetic algorithms, digital database and discrete and continuous design variables, in accordance with current design and construction practice. Several analyzes were performed to evaluate the mechanical behavior of the connections and its influence on the optimum component dimensioning. Through the presented example, concludes that this computational tool has great potential to obtain optimum dimensions for minimization of cost of connections without violating the normative and constructive constraints.

The computational tool presented here obtained significant improvements in the costs of the connections in relation to the results available in the literature, without compromising the efficiency and safety of the structure.

In history of optimization curve it is possible to observe that the mean value decreases, tending to the value of the best solution in each generation, which indicates that the algorithm converged monotonically.

This paper demonstrated, in generally, that the optimization of beam-column connections in plane steel frame has been successful. The computational tool also determines the optimized profiles automatically from the commercial profiles available in the database.

From the results obtained it is possible to conclude that the optimization model presented in this paper demonstrates to be a robust and effective tool in minimizing the cost of beam-column connections. In addition, the computational environment developed in this work is quite friendly and easy to understand, where the user can easily configure the problem input data and design constraints.

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