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Approximated Method of Nonlinear Geometric Analysis Applied to Optimum Design of Steel Frames

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Abstract

A complete process of optimizing a steel structure depends on the calculated requesting efforts, the standard considered, the profile catalogs used in the design and the optimization algorithm adopted. This study aims to optimize steel space frames structures, using the Genetic Algorithm (GA) associated with the Two Cycles Iterative Method (TCIM), for a simplified geometric nonlinear analysis. The design follows the 'Eurocode 3 – Design of Steel Structure'. The results show that the GA is efficient in optimizing steel structures by working with discrete variables facilitating the use of profile table provided by manufacturers. Regarding the consideration of second order effects in the optimization process, the use of TCIM generated accurate results, with low computational cost. The use of a more complete analysis method; the 'Eurocode 3 – Design of Steel Structure'; and different shape catalogs, according to the cases analyzed, are the reasons for the reduction observed.

Keywords: Structural optimization; Genetic algorithm; Geometric nonlinear analysis, Two cycles iterative method.

1. Introduction

Due to the improvement of processing power of computers, the use of optimization algorithms in the solution of structural engineering problems becomes increasingly common both in plane and in space structures, considering or not the effects of nonlinearities in the structure.

Usually, the solution of structural engineering problems is obtained by the designer's experience or in some cases using trial and error techniques. In this context, the use of optimization techniques allows more efficients and automatized solutions. Thus the application of optimization can reduce errors in the final design considering an safety, an economic, and an environmetal point of view. The use of optimization techniques in steel structures and composite steel/concrete structures has been growing over the last decades, as can be seen in the works of Arpini and Alves [1], Fiorotti *et al*. [2], Xin *et al*. [3], among others.

One of the most used metaheuristic algorithms is the Genetic Algorithm (GA), developed in the 1950s and related to biologist A. S. Fraser, although the work of Holland [4] had the greatest contributions since he proposed a logical approach to issues regarding the mechanism of species adaptation ([5]). Gregor Mendelian's principle of Mendelian Heredity (1866) and Charles Darwin's theory of Natural Selection (1838) inspired these algorithms, which is applied in areas such as engineering, medicine, economics, biology, chemistry.

Fu, Zhai and Zhou [6] mention the advantage of using GA in steel beam bridge projects. In addition to obtaining satisfactory results, the authors highlight that the method is efficient in representing real gains, since it is possible to use discrete variables, such as the obtained from shape tables.

Liu, Hammad and Itoh [7] apply the GA with the Pareto principle and use it in a bridge recovery study, forming a model with multiple objective functions and reconciling the various results. However, Breda, Pietralonga and Alves [5] present the formulation to steel deck optimization obtained via GA. The algorithm seeks to determine the best steel deck composition, the interaction ratio between the slab and the beams, and the automatic arrangement of the secondary beams.

In this work the algorithm seeks to determine the best composition of the composite slab, the degree of interaction between the slab and the beams and the automatic arrangement of the secondary beams.

Kripakaran, Hall and Gupta [8] develop a decision-making support system for rigid steel frames where they use an GA to generate optimized structures, varying the types of connections (rigid and labeled). In this work, the *Modeling to Generate Alternatives* (MGA) technique is used, in which the solution is chosen from a small group composed of the best answers. This improves design possibilities, since the optimal response may present inconveniences not captured by algorithm modeling and depend on the critical analysis of a human.

Prendes-Gero, Bello-García and Coz-Díaz [9] apply GA in flat and space structures and complicit the responses obtained with those generated by a commercial program of analysis and dimensioning, obtaining a 9.3% lighter response to the 2D structure and 10% for the 3D structure. Kociecki and Adeli [10] implement a modified GA to increase convergence speed, characterizing an evolutionary computing method. Then, the authors used efficiently this GA to optimize the shape of two real structures, saving between 10% and 16% of structure weight.

Meruane and Heylen [11] develop a hybrid GA and apply it in the detection of structural damage, avoiding false damage detection, which is more efficient than conventional

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methods. In a complex scenario, the algorithm analyzed only 6.3% several possibilities to detect all damage.

Forti, Souza and Requena [12] optimize plane and space steel trusses, of roofs large spanwith the GA, to improve the structural design of the system. Ramos and Alves [13] applied GA to analyze the optimum design and the collapse modes of alveolar beams.

However, the most accurate structural analysis and design – depending on the type of loading and geometry – is the analysis of the effects due to the geometric nonlinearity of the structure, especially for steel structures. Works related before were not concerned with the influence of second order effects during the optimization problem using GA. Usually, associate nonlinear analysis to an optimization problem brings large computational effort, since complete nonlinear analysis uses matrix methods, and incremental-iterative processes in an already heavy algorithm of optimization.

Therefore, to improve the structural design, this work associates optimization techniques to geometric nonlinear analysis, considering the Two Cycles Iterative Method (TCIM), an approximated method that however, uses a geometric matrix.

Rodrigues, Burgos and Martha ([14], [15]) present a new approach to the Timoshenko geometric stiffness matrix considering higher-order terms in the strain tensor. The authors had excellent results from the point of view of the precision of the values for the displacements, but with a high computational cost.

There are studies that associate stability analysis to structural optimization as Lu, Gilbert and Tyas [16], where the authors conclude that the ratio between gravitational and horizontal forces exert great influence on the determination of the optimal frame, as well as the code chosen for sizing. This shows the need to compare optimized structures generated by the Brazilian code with those generated by international codes.

Hernández-Montes, Gil-Martín and Aschheim [17] create an algorithm to optimize frame elements, using the approximate method of second-order analysis from AISC Load Resistance Factor Design (AISC-LRFD [18]) and Eurocode 3 [19] and the B1-B2 Method the study developed a tool capable of achieving a great increase in structural stability with a small increase in the structure's weight.

Hellesland [20] cites the inefficiency of some approximate methods in predicting local second-order effects, P-δ, in elements subjected to simple curvature. The possible reasons for this difference are the P-□ effects, which are higher than those usually considered, this affects the stiffness distribution at the column´s edge. Then the author proposes an amplification coefficient to correct the values and to approximate to the real values.

Jing and Jinxin [21] propose a formulation to estimate the effective bending stiffness, used in an approximate method of second-order analysis and applied to concrete frames. They obtained more accurate and faster results compared to the old formulation, because they avoid extensive calculations based on the solutions of differential equations. This demonstrates the importance of approximate methods, especially when applied in iterative algorithms, in which a small simplification in calculations can represent an exponential gain in analysis time.

Although several researches with the application of structural optimization techniques have been presented over the last few years, usually the analysis of the effect of geometric nonlinearity is performed by approximated methods as Load Resistance Factor Design, and the B1-B2 method, since a complete nonlinear analysis would be very costly in an optimization problem. However the TCIM is approximated matrix method easily implemented in a linear finite element analysis program.

Therefore, this study aimed to present the problem formulation of steel space frames structural optimization according to EN 1993-1-1 [19] and considering geometric nonlinearity. The solution of the optimization problem is via Genetic Algorithm and the geometric nonlinear analysis was performed via TCIM.

2. Formulation of the Optimization Problem

This study seeks to minimize the structure's weight, thus, the objective function is represented by the expression (1):

$$Weight = \sum_{i=1}^{n} L_i . A_i . \rho \tag{1}$$

where: n *is the number* of elements; L_i length of element i, in m; A_i cross-section area of element i, in m^2; ρ specific mass of steel, adopted as 7860 kg/^{m3}.

2.1. Constraints

The constraints applied to the solutions of the structural dimensioning problem are directly related to the normative criteria of EN 1993-1-1. 2005 [19] linked to both The Ultimate (ULS) and Service (SLS) States. In this way, the constraints to be used in this problem are presented in the (2) representing the Ultimate Limit State and the constraints (3). Serviceability Limit State.

$$ULS = \begin{cases} C_1: \frac{N_{Ed}}{N_{Rd}} - 1 \leq 0 \; - \; Axial\ force \\ C_2: \frac{V_{y,Ed}}{V_{y,c,Rd}} - 1 \leq 0 \; - Shear\ effort\ axis\ y \\ C_3: \frac{V_{z,Ed}}{V_{z,c,Rd}} - 1 \leq 0 \; - \; Shear\ effort\ \ axis\ \ z \\ C_4: \frac{M_{y,Ed}}{M_{y,Rd}} - 1 \leq 0 \; - \; Bending\ moment\ \ axis\ y \\ C_5: \frac{M_{z,Ed}}{M_{z,Rd}} - 1 \leq 0 \; - Bending\ moment\ axis\ \ z \\ C_6: \frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed}}{M_{y,Rd}} + \frac{M_{z,Ed}}{M_{z,Rd}} - 1 \leq 0 - Combined\ bending \\ C_7: \frac{M_{y,Ed}}{M_{y,N,Rd}} - 1 \leq 0 \; - Bending\ moment\ axis\ y\ and\ axial \\ C_8: \frac{M_{z,Ed}}{M_{z,N,Rd}} - 1 \leq 0 \; - Bending\ moment\ axis\ z\ and\ axial \\ C_9: \left(\frac{M_{y,Ed}}{M_{y,Rd}}\right)^{\alpha} + \left(\frac{M_{z,Ed}}{M_{z,Rd}}\right)^{\beta} - 1 \leq 0 \; - \; Bending\ moment\ a□□es\ y\ and\ z \\ C_{10}: \frac{h_w/t_w}{72\varepsilon/\eta} - 1 \leq 0 \; - Section\ without\ stiffeners \\ C_{11}: \frac{Class}{2} - 1 \leq 0 \; - selects\ class\ 1,2 \end{cases} \tag{2}$$

$$SLS = \begin{cases} C_{12}: \frac{u_x}{u_{x,lim}} - 1 \leq 0 \; - \; Node\ displacement\ x \\ C_{13}: \frac{u_y}{u_{y,lim}} - 1 \leq 0 \; - \; Node\ displacement\ y \\ C_{14}: \frac{u_z}{u_{z,lim}} - 1 \leq 0 \; - \; Node\ displacemet\ z \\ C_{15}: \frac{\delta_y}{\delta_{y,máx}} - 1 \leq 0 \; - \; Maximum\ deflection\ \ y \\ C_{16}: \frac{\delta_z}{\delta_{z,máx}} - 1 \leq 0 \; - \; Maximum\ deflection\ z \end{cases} \tag{3}$$

To solve the optimization problem the GA algorithm was adopted. The considered initial population contains 120 individuals, the rate of elite individuals and crossing of the intermediate type are 0.05 and 0.8, respectively, whereas the mutation rate is random.

2.2. Analysis of Geometric Nonlinearity via TCIM

The TCIM is a method of analysis that considers geometric nonlinearity in a simplified way and presented by Chen and Lui [22]. The method, although simplified, if used correctly is applicable to three-dimensional structures with good results.

The equilibrium equation to perform a geometric nonlinear structural analysis using TCIM is shown in equation (4). The tangent stiffness matrix is given by the sum of the linear stiffness matrix (5) and the geometric stiffness matrix (6).

$$\{F\} = [K_L + K_G].\{D\} \tag{4}$$

$$K_L = \begin{bmatrix}
\frac{EA}{L} & 0 & 0 & 0 & 0 & 0 & -\frac{EA}{L} & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{12EI_Z}{L^3} & 0 & 0 & 0 & \frac{6EI_Z}{L^2} & 0 & -\frac{12EI_Z}{L^3} & 0 & 0 & 0 & \frac{6EI_Z}{L^2} \\
0 & 0 & \frac{12EI_Y}{L^3} & 0 & -\frac{6EI_Y}{L^2} & 0 & 0 & 0 & -\frac{12EI_Y}{L^3} & 0 & -\frac{6EI_Y}{L^2} & 0 \\
0 & 0 & 0 & \frac{GI_X}{L} & 0 & 0 & 0 & 0 & 0 & -\frac{GI_X}{L} & 0 & 0 \\
0 & 0 & -\frac{6EI_Y}{L^2} & 0 & \frac{4EI_Y}{L} & 0 & 0 & 0 & \frac{6EI_Y}{L^2} & 0 & \frac{2EI_Y}{L} & 0 \\
0 & \frac{6EI_Z}{L^2} & 0 & 0 & 0 & \frac{4EI_Z}{L} & 0 & -\frac{6EI_Z}{L^2} & 0 & 0 & 0 & \frac{2EI_Z}{L} \\
-\frac{EA}{L} & 0 & 0 & 0 & 0 & 0 & \frac{EA}{L} & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{12EI_Z}{L^3} & 0 & 0 & 0 & -\frac{6EI_Z}{L^2} & 0 & \frac{12EI_Z}{L^3} & 0 & 0 & 0 & -\frac{6EI_Z}{L^2} \\
0 & 0 & -\frac{12EI_Y}{L^3} & 0 & \frac{6EI_Y}{L^2} & 0 & 0 & 0 & \frac{12EI_Y}{L^3} & 0 & \frac{6EI_Y}{L^2} & 0 \\
0 & 0 & 0 & -\frac{GI_X}{L} & 0 & 0 & 0 & 0 & 0 & \frac{GI_X}{L} & 0 & 0 \\
0 & 0 & -\frac{6EI_Y}{L^2} & 0 & \frac{2EI_Y}{L} & 0 & 0 & 0 & \frac{6EI_Y}{L^2} & 0 & \frac{4EI_Y}{L} & 0 \\
0 & \frac{6EI_Z}{L^2} & 0 & 0 & 0 & \frac{2EI_Z}{L} & 0 & -\frac{6EI_Z}{L^2} & 0 & 0 & 0 & \frac{4EI_Z}{L}
\end{bmatrix} \tag{5}$$

$$K_G = \begin{bmatrix}
\frac{P}{L} & 0 & 0 & 0 & 0 & 0 & -\frac{P}{L} & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{6P}{5L} & 0 & 0 & 0 & \frac{P}{10} & 0 & -\frac{6P}{5L} & 0 & 0 & 0 & \frac{P}{10} \\
0 & 0 & \frac{6P}{5L} & 0 & -\frac{P}{10} & 0 & 0 & 0 & -\frac{6P}{5L} & 0 & -\frac{P}{10} & 0 \\
0 & 0 & 0 & \frac{J_pP}{AL} & 0 & 0 & 0 & 0 & 0 & -\frac{J_pP}{AL} & 0 & 0 \\
0 & 0 & -\frac{P}{10} & 0 & \frac{2PL}{15} & 0 & 0 & 0 & \frac{P}{10} & 0 & -\frac{PL}{30} & 0 \\
0 & \frac{P}{10} & 0 & 0 & 0 & \frac{2PL}{15} & 0 & -\frac{P}{10} & 0 & 0 & 0 & -\frac{PL}{30} \\
-\frac{P}{L} & 0 & 0 & 0 & 0 & 0 & \frac{P}{L} & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{6P}{5L} & 0 & 0 & 0 & -\frac{P}{10} & 0 & \frac{6P}{5L} & 0 & 0 & 0 & -\frac{P}{10} \\
0 & 0 & -\frac{6P}{5L} & 0 & \frac{P}{10} & 0 & 0 & 0 & \frac{6P}{5L} & 0 & \frac{P}{10} & 0 \\
0 & 0 & 0 & -\frac{J_pP}{AL} & 0 & 0 & 0 & 0 & 0 & \frac{J_pP}{AL} & 0 & 0 \\
0 & 0 & -\frac{P}{10} & 0 & -\frac{PL}{30} & 0 & 0 & 0 & \frac{P}{10} & 0 & \frac{2PL}{15} & 0 \\
0 & \frac{P}{10} & 0 & 0 & 0 & -\frac{PL}{30} & 0 & -\frac{P}{10} & 0 & 0 & 0 & \frac{2PL}{15}
\end{bmatrix} \tag{6}$$

Wherein, P is the element axial force; E is the element Young’s modulus; A is the element cross-section area; L is the element length; I is the element moment of inertia; J_p is the torsion constant of Saint Venant; *x, y,* and *z* are the cartesian axes. Figure 1 presents the flowchart for the use of the TCIM method and Figure 2 presents the flowchart of the optimization process.

3. Numerical Analysis

3.1. Validation of the 2 Cycles Interactive Method

ANSI/AISC 360-16 [23] presents two structural cases with precise structural analysis results so that they are used as a reference in the initial evaluation of methods and second-order analysis programs. Case 1 (figure 3) aims to evaluate the P-δ effect, and Case 2 (Figure 4) the P-δ and mainly P-Δ effects.

Through these cases it is possible to evaluate whether the studied method correctly considers the P-δ and P-Δ effects in the calculation of requesting efforts and structural deformations, the first being neglected by many methods of second-order analysis.

For the analyses, the Profile W360x72 was used for both cases; bending columns in relation to the axis of greatest inertia; and modulus of elasticity E = 200 GPa. An analysis of the bar discretization was performed as follows.

3.2. Discretization Analysis of the Elements

To verify the accuracy of the solution of the reference cases, the discretization of the elements was evaluated. The bars were analyzed as a single element and subdivided into 2, 4, 8 and 16 elements. Figure 5 shows the results relative to the maximum bending moment and displacements for Cases 1 and 2.

In this analysis, the overlapped graphs facilitate the visualization of the time and error associated with each degree of discretization, represented on the horizontal axis. The error plot is represented by the bars and associated with the left vertical axis, with the limits recommended by ANSI/AISC 360-16 [23], represented by the dashed red lines. The line chart represents the analysis time and is associated with the right vertical axis.

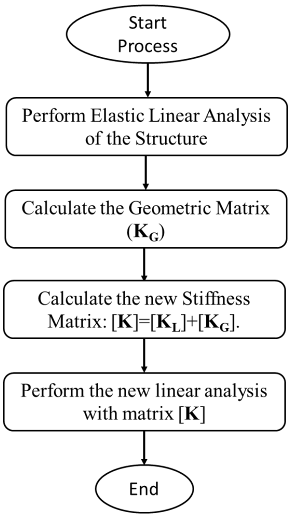


Fig. 1. Flowchart for TCIM.

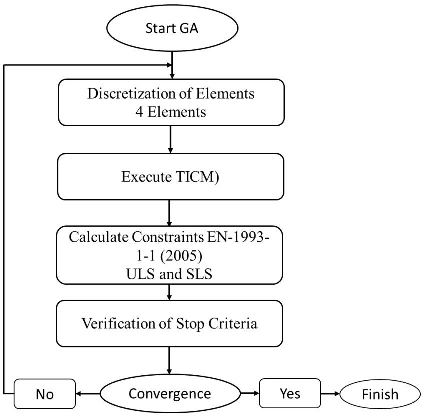


Fig. 2. Flowchart of Optimization Process.

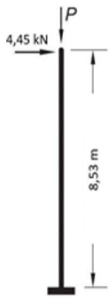
Although the precision increase, by subdividing the bar into more than four elements, the analysis time follows the proportionality in relation to the number of subdivisions. Thus, four elements were adopted for discretization, which brings the best balance between precision and computational cost, considering the results obtained in the discretization analysis.

Figure 6 presents the results of the analyses for the 1st Reference Model, considering the moment at the bottom of the column, and the the maximum displacements at the top of the column. The table 1 shows the percentual difference between results.

Axial force, P [kN]	0	667	1334	2001
M_{medium} [kN.m]	26.6 [26.6]	30.5 [30.4]	35.7 [35.4]	43.0 [42.4]
u_{medium} [mm]	5.13 [5.02]	5.86 [5.71]	6.84 [6.63]	8.21 [7.91]

Analysis includes axial, shear and bending deformations.
[Values in brackets] exclude shear deformation.

Fig. 3. Reference Case 1.



Axial force, P [kN]	0	445	667	890
M_{base} [kN.m]	38.0 [38.0]	53.2 [53.1]	68.1 [67.7]	97.2 [96.2]
u_{topo} [mm]	23.1 [22.9]	34.2 [33.9]	45.1 [44.6]	66.6 [65.4]

Analysis includes axial, shear and bending deformations.
[Values in brackets] exclude shear deformation.

Fig. 4. Reference Case 2.

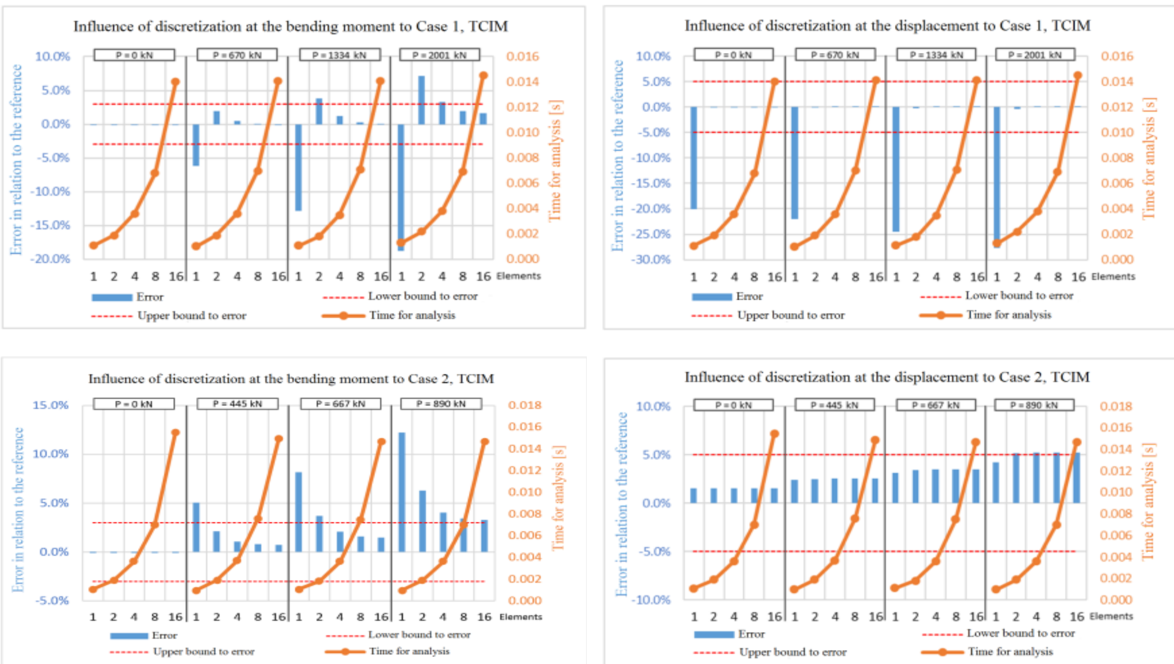


Fig. 5. Evaluation of the structural discretization.

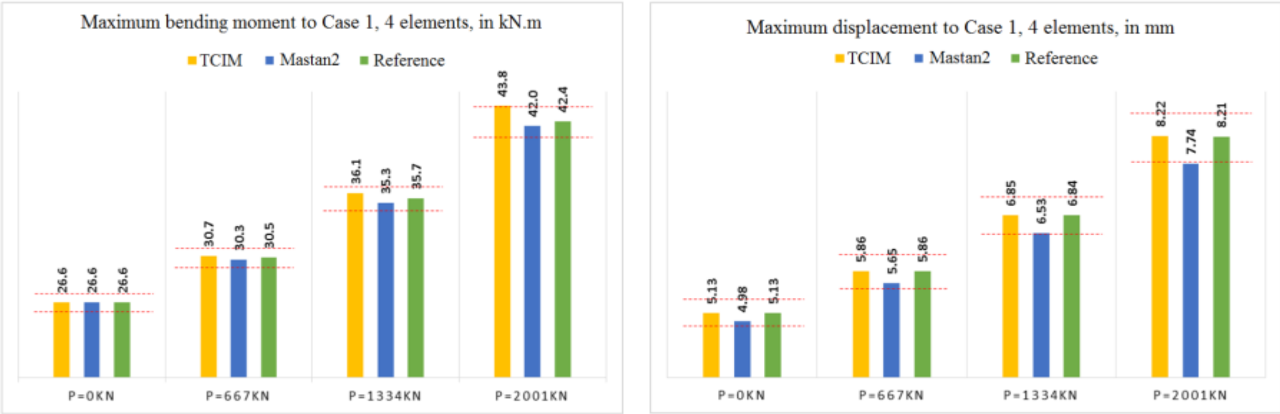


Fig. 6. Results of the bending moment (kN.m) and maximum displacement (mm) of Case 1, discretization of 4 elements.

Table 1. Analysis of the Results.

Axial force, P [kN]		**0**	**667**	**1334**	**2001**
M_{base}	AISCI	26.6	30.5	35.7	42.4
[kN.m]	TCIM	26.6	30.7	36.1	43.8
u_{topo}	AISCI	5.13	5.86	6.84	8.21
[mm]	TCIM	5.13	5.86	6.85	8.22

As can be observed the difference between the reference model and the TCIM for all cases of loads was less than 3.2% (dashed red lines).

Similarly, Figure 7 presents the results for maximum bending moment obtained by the modules and the difference from the reference values for Case 2. The table 2 shows a comparative analysis, subdividing the bars into 4 elements. For all cases the limits referring to the deviation of ±3% are represented in dashed red lines.

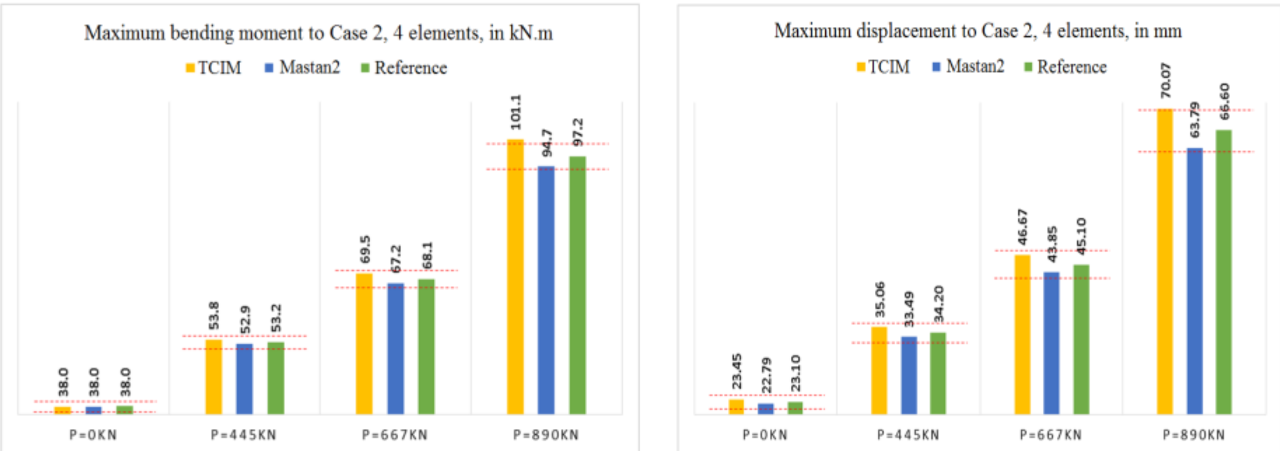


Fig. 7. Results of the bending moment (kN.m) and maximum displacement (mm) of Case 2, discretization of 4 elements.

Table 2. Comparative analysis of case 2.

Axial force, P [kN]		**0**	**445**	**667**	**890**
M_{base}	AISCI	38	53.2	68.1	97.2
[kN.m]	TCIM	38	53.8	69.5	101.1
u_{topo}	AISCI	23.1	34.2	45.1	66.6
[mm]	TCIM	23.45	35.06	46.67	70.07

Table 2 shows that the TCIM presents a good precision being within the orientation limit of the ANSI/AISC 360-16 [20], except for the case of higher axial load and this difference was 5% superior, thus showing that the method is more conservative in determining moments and displacements.

3.3. Optimization of Plane Frame Presented in Farshchin et al. [24].

The first example analyzed is the frame presented in Farshchin *et al*. [24] and shown in the bars are grouped into columns and beams, f_y is taken with the value of 250 MPa and E equal to 200 GPa. The authors used the method called *School Based Optimization to* determine the optimal solution to the problem.

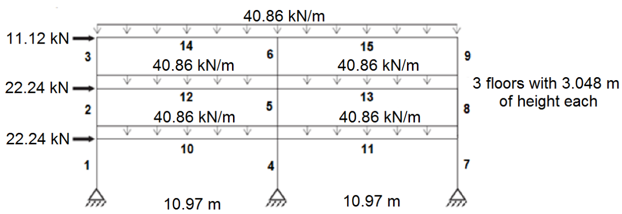


Fig. 8. Plane frame by Farshchin et al. [24]. (Source: adapted from Farshchin *et al*., [24])

Farshchin *et al*. [24] does not limit the displacement of the structure in this example. In addition to the grouped bars, the profiles of the columns are limited to the W10 of the American standard, which have total section height ranging between 250 mm and 290 mm, this constraint is added exclusively in this example. Table 3 shows the results obtained by the program elaborated with different catalogs of profiles and those obtained by Farshchin *et al*. [24], taken as a reference.

Table 3. Optimization results of the frame of Farshchin et al. [24].

Parameter	Farshchin *et al.* [24]	Authors	Authors	Authors
Optimization method	*School Based Optimization*	Genetic Algorithm	Genetic Algorithm	Genetic Algorithm
Standard	AISC-LRFD (2001)	EN 1993-1-1 (2005)	EN 1993-1-1 (2005)	EN 1993-1-1 (2005)
Method of analysis	FIELD	Approximate 2nd order - TCIM	Approximate 2nd order - TCIM	Approximate 2nd order - TCIM
Catalogue	W profiles of the AISC-LRFD [25]	W profiles of the AISC-LRFD [25]	Gerdau® laminates	European laminates
Column profile	W250x89	W250x101	W250x101	HEM240
Beam profile	W610x92,3	W530x82,0	W530x82,0	IPE500
Optimization Weight (Difference)	8523.9 kg	8181.4 kg (-4,0%)	8192.5 kg (-3,9%)	10281.4 kg (+20,6%)

The result obtained with the Gerdau laminate table® shows a small reduction in relation to the result of Farshchin *et al.* [24], which can be explained by the method of analysis. It is noted that the answer found using the AISC-LRFD W Profiles catalogue [25] is the same as with Gerdau's laminate table®, and the small difference between the total weights of the structure caused by rounding of the tables.

On the other hand, the result obtained with the Table of European Profiles presents a result 20.6% higher than the result of Farshchin *et al.* [24]. This is due to the constraint on the size of the columns because this table presents only 8 elements that meet the limitation imposed by the project, against the 18 available by the Catalog of W Profiles of the AISC-LRFD [25] and 14 for the laminate table of Gerdau®.

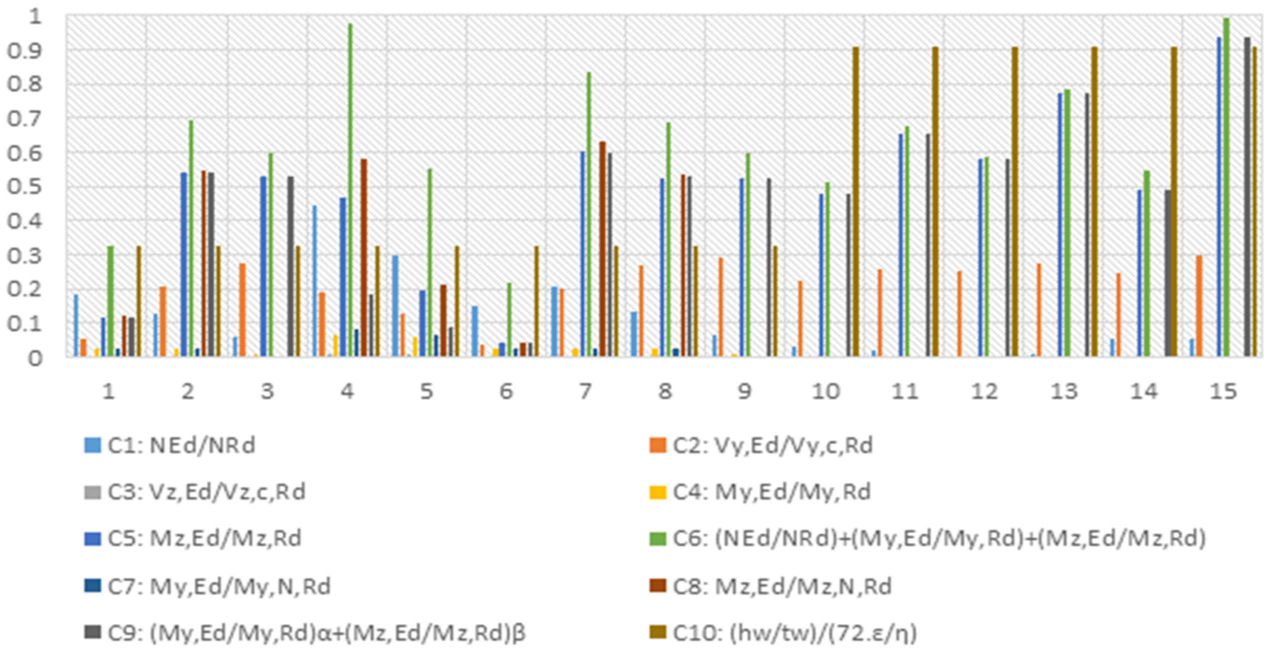


Fig. 9. Constraints for the plane frame analyzed with Gerdau® laminate profiles.

It was observed for all cases that the governing criterion in the design of the columns (bars 1 to 9), of this example was that of the combined bending, given by equation 6 and represented by the constraint C_6 in the system. This constraint refers to column 4, the most requested. For the beams (bars 10 to 15) it was the same criterion acting on beam 15. The analysis of the constraints follows in Figure 9 for Gerdau® profiles.

3.4. Spatial Frames Optimization

The second example is of a space frame presented in Figure 10 and proposed by McGuire, Gallagher and Ziemian [26].

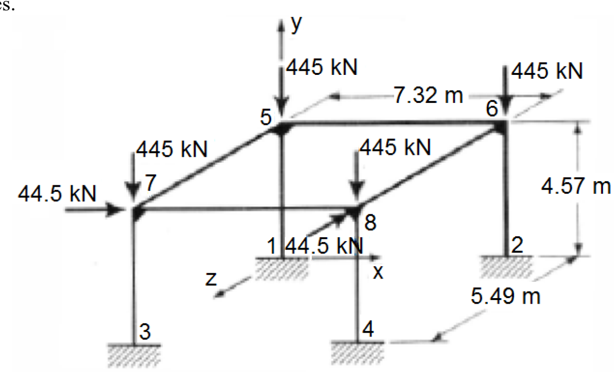


Fig. 10. Example proposed by McGuire, Gallagher and Ziemian [26].

The results obtained with the program elaborated in this work, using the catalog of Gerdau® laminate profiles and laminates of the European standard, are presented in Table 2

Table 4. Spatial frame optimization results.

Parameter	Author	Author	Author
Standard	NBR 8800:2008 [27]	EN 1993-1-1 (2005)	EN 1993-1-1 (2005)
Method of analysis	Effective lengths (1º Order) $K_x = 1$, $K_y = 1$, $K_z = 1$	Approximate 2nd order - TCIM	Approximate 2nd order - TCIM
Catalogue	Gerdau® laminates	Gerdau® laminates	European laminates
Profiles	1. HP200x53.0 (H) 2. HP250x62.0 (H) 3. W460x89,0 4. W360x91.0 (H) 5. W200x19,3 6. W200x52.0 (H) 7. W150x22,5(H) 8. W200x26,6	1. W150x29.8 (H) 2. W360x64,0 3. W200x31,3 4. W610x140,0 5. W200x15,0 6. W150x13,0 7. W200x15,0 8. W310x28,3	1. HEB140 2. IPE130 3. HEA160 4. HEB320 5. IPE80 6. IPE80 7. IPE80 8. IPE180
Total weight (Difference)	2147.2 kg	1668.8 kg (-22,3%)	1322.3 kg (-38,4%)

The use of Effective Lengths Method with K coefficients *equal* to 1 in the analysis of a spatial gantry is an approximation, since the table implemented in this program should be used in insulated bars, however, it is considered, in this case, that the beams offer a good locking to the horizontal and rotational displacement of the tops of the columns.

There is a considerable reduction using the elaborate program. This difference, once again, can be caused by the method of analysis used and this time there is also a considerable difference between the catalogues used by the elaborated program.

Figure 11 constraints for the case analyzed with Gerdau® profiles for the imperfections considered in the x-axis and for the imperfections considered in the z-axis, respectively.

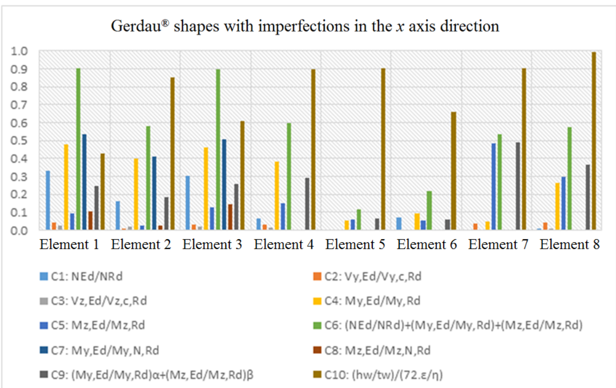


Fig. 11. Constraints for the spatial frame analyzed with Gerdau® profiles and imperfections in the direction of the x-axis.

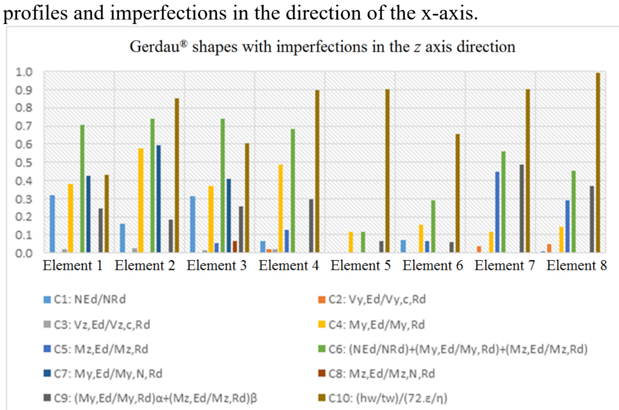


Fig. 12. Constraints for the spatial frame analyzed with Gerdau® profiles and imperfections in the direction of the z-axis.

3.5. Analysis of Profiles Catalogues

Considering the difference obtained in the final solutions, the graphics in Figures 13, 14 and 15 were generated. The presented figures display the profiles of these two tables (Gerdau® and European laminates) ordered in relation to the cross-sectional area, and the plastic resistance modules in relation to the *y* and *z* axes, respectively, in order to observe characteristics of these tables.

As shown in Figures 13, 14 and 15, the European profiles have a wider distribution, having the smallest and largest profiles for the quantities considered. The cross-sectional area is directly linked to the linear mass of the element and to the resistance of axial loads. The plastic resistance modules are directly linked to resistance to bending stress in relation to the respective axes.

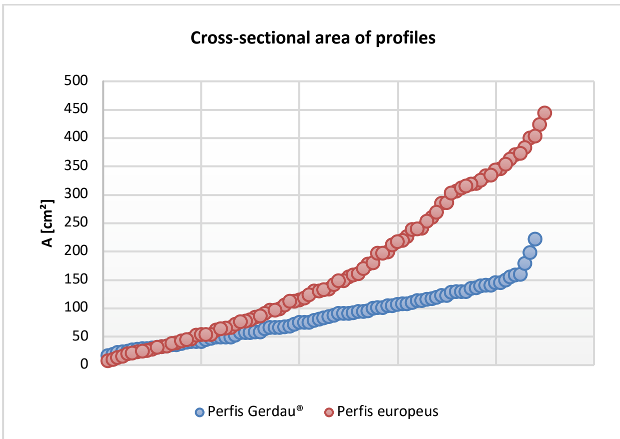


Fig. 13. Gerdau® and European profiles ordered according to the cross-section area.

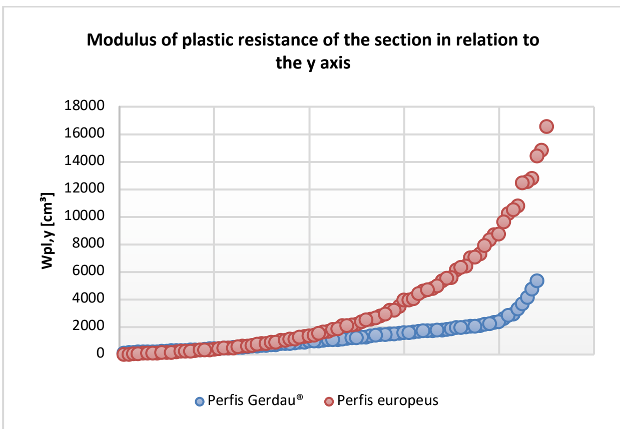


Fig. 14. Gerdau® and European profiles ordered according to the cross-section plastic resistance module related to the y axis.

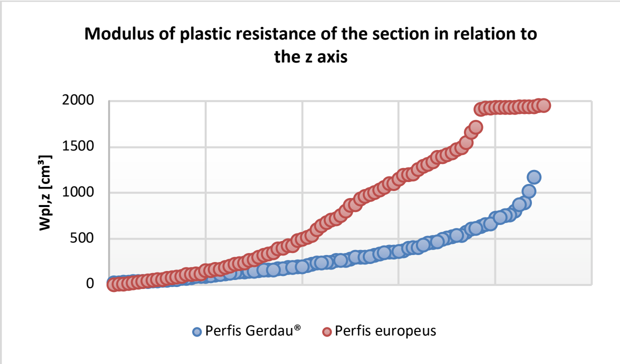


Fig. 15. Gerdau® and European profiles ordered according to the cross-section plastic resistance module related to the z axis.

It can be concluded that for the studied cases, the European catalog had an advantage in structures with elements without direct loading on them, because it has lighter profiles. However, this advantage is not observed, in cases where all elements have direct loading, as example, in the optimization of the plane frame, the first example. In this case, the Gerdau® profile catalog achieved better results by having a greater number of profiles at the resistance level closest to the requesting loads.

4. Conclusions

The applications developed in this work allow us to verify that it is feasible to create a structural analysis that makes second order analysis using approximate methods with good precision and that optimizes the structural design according to EN-1993-1-1[16] via AG.

The TCIM demonstrated good accuracy in determining the requesting efforts and structural displacements when compared to the reference cases of ANSI/AISC 360-16 [21], mainly for structures subjected to a loading level for which they are usually sized, also presenting a low increase in computational demand, when compared to the first-order analysis. This low computational cost has a direct impact on the analysis and optimization of larger structures, considering that the currently most used algorithms are bioinspired methods and generally work with a population of individuals, and in each step of the iterative process the solution will be analyzed several times.

As for structural optimization, the GA proved to be effective when applied to isolated bar structures, flat frames and spatial frames, presenting coherent results when compared with literature results using EN 1993-1-1 [16] and Effective Length Method.

With the results it was possible to observe reduction in the weight of the structure when using different methods of structural analysis and the differences and particularities of the implemented catalogs. This observed reduction may also be related to the standard adopted. Reductions are observed when analyzing structures without the grouping of elements, but there are many constructive and structural advantages associated with the grouping of elements.

Finally, is the importance of considering the second order effects in structural analysis, as these can be determinant factors in the structural design, as exemplified in this work. The implementation of the method can be done directly in commercial programs, due to its easy implementation, and adaptation of linear finite element codes. Also, the low computational cost opens possibilities for analysis in more robust structures.

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