Approximated method of nonlinear geometric analysis applied to steel frames designed by Eurocode 3 and optimized with Genetic Algorithm

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Abstract. Structural optimization is a process that can demands high data processing power depending on the algorithm adopted. In addition, a rigorous geometric nonlinear analysis is performed with iterative numerical algorithms increasing computational efforts. In order to reduce the amount of data to be processed, the Two Cycles Iterative Method (TCIM) is implemented in the Structures3D (S3D), an optimization software under development in Matlab® using its Genetic Algorithm (GA). The structural analysis, carried out in accordance to Eurocode 3, is also implemented in S3D to improve it as well. The final product is an optimization module that take in account, by approximation, the geometric non-linearity and design by Eurocode 3 of steel structures. An example of application of this module is presented and the result obtained is compared with other author.

Keywords: Genetic Algorithm, Steel Structures, Geometric Nonlinear Analysis.

1 Introduction

Engineering projects has always aimed to reach maximum efficiency in the use of resources. With this in mind, in steel structure projects, the Genetic Algorithm (GA) is an adequate tool to achieve rational use of the material without giving up safety. Studies like Prendes-Gero *et al.* [1], Kripakaran, Hall and Gupta [2] and Breda, Pietralonga and Alves [3] show the application of GA obtaining gains when compared to other methods.

The efficiency of GA in optimizing steel structures is due to the method's capacity to working with discrete variables, which makes it compatible with the tables of structural steel shapes. Fu, Zhai and Zhou [4] demonstrated this in a study were they used GA in steel girder bridge designs.

However, the second order effects has always been difficult to take in account in steel design by the majority of optimization methods. A rigorous second order analysis can generate substantial computational effort due to the large number of interactions required. Therefore, in this work, the Two Cycles Iterative Method (TCIM), an approximate method of second order analysis developed by Chen and Lui [5], is applied. The TCIM stands out for its simplicity of implementation and for using the geometric nonlinearity matrix, generally used in rigorous methods, although, it simplifies the rigorous process, limiting the execution to only two iterations.

In addition to the optimization method, the chosen code for the structural analysis also exerts great influence on the results obtained. According to Silva [6], which makes a comparison between different codes when carrying out a study on element buckling under compression, the current NBR 8800:2008 [7] is based on the ANSI/AISC 360-05 [8]. Bernuzzi, Cordova and Simoncelli [9], on the other hand, carried out a study comparing the EN 1993-1-1 [10] to the ANSI/AISC 360-10 [8] in the optimization of rigid frames, concluding that the American code is more conservative than the European Code.

With this in mind, it is expected that the EN 1993-1-1 [10] will lead the optimization to lighter structures, since it proved, in the mentioned studies, to be less conservative than ANSI/AISC 360-05 [8] and, consequently, than the NBR 8800:2008 [7]. Therefore, the EN 1993-1-1 [10] is the code adopted in this work.

The module in this study is implemented in Structure3D (S3D), which is a software that makes structural analysis, design and optimization of steel structures. The S3D is under development at the Federal University of Espírito Santo (UFES). Lazzari, Calenzani and Alves [11] present applications of the S3D.

Currently, the S3D performs only first order structural analysis using the Finite Element Method and it adopts the limit state method according to NBR 8800:2008 [7]. The optimization methods already implemented are the Sequential Quadratic Programming, the Method of Interior Points and the GA.

Thus, the objective of this study is to create an approximate second order analysis module based in the TCIM and then implement it in S3D. This module considers the structural geometric nonlinearity according to EN-1993-1-1 [10]. The module developed is applied in the analysis of a steel frame.

2 Methodology

2.1 Code and method used in analysis

The considerations made to the structural analysis with EN-1993-1-1 [10] are presented in Pimentel [12] and Pimentel [13] in its Method 1. In it, the author mentions that if the second order global structural analysis considers both effects of P-δ and P-Δ together with the local and global imperfections, than the individual stability of the elements does not need to be verified. To account the lateral buckling with torsion effect, the analysis need to be done also outside of the buckling plane.

As for the structural analysis, the TCIM implemented is summarized in Figure 1, adapted from Silva, Menezes and Martha [14].

<Step 1>: Perform a first order elastic analysis on the structure, obtaining the axial forces of the elements.

<Step 2>: Calculate the structural geometric stiffness matrix of the structure [K_G] with the forces obtained in the previous step.

<Step 3>: Calculate the stiffness matrix [K], obtained by the sum of the elastic stiffness matrix and the geometric stiffness matrix: [K] = [K_L] + [K_G].

<Step 4>: Perform a new linear elastic analysis on the structure, using the matrix [K], obtaining the design efforts and structural displacements.

Figure 1. Simplified procedure of TCIM (Source: adapted from Silva, Menezes and Martha [14]).

The eq. (1) presents the equilibrium equation used in the first order elastic structural analysis, considering the load vector {F}, the linear elastic stiffness matrix [k_L] and the displacement vector {D}, developed in McGuire, Gallagher and Ziemian [14].

$$\{F\} = [k_L].\{D\} \tag{1}$$

The geometric stiffness matrix of the structure [K_G] is developed from the geometric stiffness matrix of the element [k_G] presented in McGuire, Gallagher and Ziemian [14].

2.2 Optimization method

The platform used for S3D development, the Matlab® [16], provides an optimization tool that uses the GA. A possible answer for the optimization problem is a vector, also called individual, which contains the shapes of each structure element. The configuration of some GA parameters are:

- Type of population: Double vector;
- Creation function: Feasible population;
- Scaling function: Rank;
- Selection function : Stochastic uniform;
- Elite count: 5% of population size;

- Cross-over fraction: 80% of population size;
- Mutation rate: 15% of population size;
- Nonlinear constraints algorithm: Augmented Lagrangian (initial penalty equal to 10 and penalty factor equal to 100).

The population, a group of individuals, has its size set to 200 individuals, in general. But, if the number of structural elements is less than or equal to five, than the population size is set to 50 individuals.

The stopping criterion adopted is the small variation in the best response in a given number of generations (*MaxStallGenerations*), with limit value set to 100 generations.

The individuals are evaluated according to their total structural weight and compliance with security criteria, calculated with the fitness function and restrictions, respectively.

2.3 Fitness function

The fitness or objective function is the total weight of the structure, given by eq. (2).

$$Weight = \sum_{i=1}^{n} L_i . A_i . \rho \tag{2}$$

where:

n number of structural elements;
L_i length of i element, meters;
A_i cross-sectional area of i element, in square meters;
ρ specific weight of steel, adopted as 7860 kg/m³.

2.4 Constraints

The constraints of the optimization problem, in general, are related with the security criteria of Ultimate Limit States (ULS) and the Service Limit States (SLS) from EN 1993-1-1 [10]. The ULS related constraints are presented by eq. 3.

$$C_{ULS} = \begin{cases} C_1 = \dfrac{N_{Ed}}{N_{Rd}} \leq 1 \ axial\ force \\ C_2 = \dfrac{V_{y,Ed}}{V_{y,c,Rd}} \leq 1 \ shear\ force - y\ axis \\ C_3 = \dfrac{V_{z,Ed}}{V_{z,c,Rd}} \leq 1 \ shear\ force - z\ axis \\ C_4 = \dfrac{M_{y,Ed}}{M_{y,Rd}} \leq 1 \ bending\ moment - y\ axis \\ C_5 = \dfrac{M_{z,Ed}}{M_{z,Rd}} \leq 1 \ bending\ moment - z\ axis \\ C_6 = \dfrac{N_{Ed}}{N_{Rd}} + \dfrac{M_{y,Ed}}{M_{y,Rd}} + \dfrac{M_{z,Ed}}{M_{z,Rd}} \leq 1 \ combination\ of\ efforts \\ C_7 = \dfrac{M_{y,Ed}}{M_{y,N,Rd}} \leq 1 \ bending\ moment\ with\ axial\ force - y\ axis \\ C_8 = \dfrac{M_{z,Ed}}{M_{z,N,Rd}} \leq 1 \ bending\ moment\ with\ axial\ force - z\ axis \\ C_9 = \left(\dfrac{M_{y,Ed}}{M_{y,Rd}}\right)^{\alpha} + \left(\dfrac{M_{z,Ed}}{M_{z,Rd}}\right)^{\beta} \leq 1 \ bi-axial\ bending\ moment - y\ and\ z\ axis \\ C_{10} = \dfrac{h_w/t_w}{72\,\varepsilon/\eta} \leq 1 \ shapes\ without\ stiffeners \\ C_{11} = \dfrac{Class}{2} \leq 1 \ shapes\ of\ class\ 1\ and\ 2 \end{cases} \tag{3}$$

Likewise, the SLS related constraints are presented by eq. 4.

$$C_{SLS} = \begin{cases} C_{12} = \dfrac{u_x}{u_{x,lim}} \leq 1 \; node\ displacement - x\ direction \\ C_{13} = \dfrac{u_y}{u_{y,lim}} \leq 1 \; node\ displacement - y\ direction \\ C_{14} = \dfrac{u_z}{u_{z,lim}} \leq 1 \; node\ displacement - z\ direction \\ C_{15} = \dfrac{\delta_y}{\delta_{y,máx}} \leq 1 \; beam\ deflection - y\ direction \\ C_{16} = \dfrac{\delta_z}{\delta_{z,máx}} \leq 1 \; beam\ deflection - z\ direction \end{cases} \quad (4)$$

The constraints number 10 and 11 are responsible for select shapes that do not need web stiffeners and shapes from classes 1 and 2, respectively. These considerations were made for simplification of search space.

2.5 Search space

The possible answers to this optimization problem are obtained from the European laminated table of shapes, in the following types: IPE, 18 elements, HEA, 24 elements, HEB 24 elements and HEM, 24 elements. Totaling 90 elements, obtained from Eurocode Applied [17].

Other considerations and details of the GA configuration used, options that the codes offers for this type of analysis and table of shapes can be found in Breda [18].

3 Application

Sánchez- Olivares and Espín [19] present the steel frame analyzed, which is shown in Figure 2

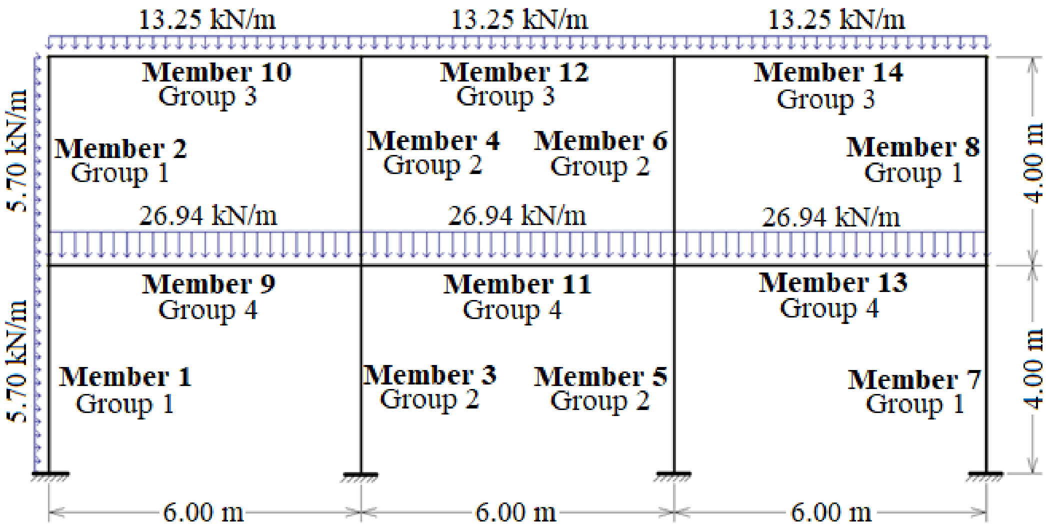

Figure 2. The maximum horizontal displacement allowed for this frame is *H*/420 (1.90 cm), where *H* is the total height of the frame and the maximum deflection allowed for the beams is limited to *L*/250 (2.40 cm), where *L* is the span of the beam. It is adopted f_y equal to 275 MPa and *E* equal to 210 GPa. The elements are grouped into group 1, outer columns, group 2, inner columns, group 3, roof beams and group 4, floor beams.

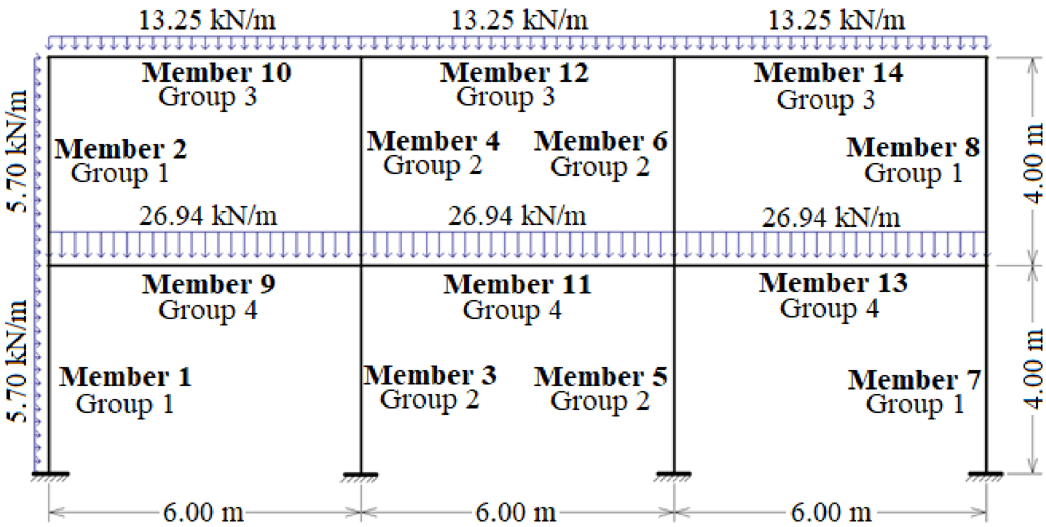

Figure 2. Steel frame analyzed. (Source: adapted from Sánchez-Olivares and Espín [19]).

The software created by Sánchez-Olivares and Espín [19] varies the connections stiffness, but the module developed in this work does not have this functionality. So, the result obtained will be compared just to the version with rigid connections.

The Table 1 presents the results of Sánchez-Olivares and Espín [19] taken as a reference and compared with the module developed.

Table 1. Optimization results.

Parameter	Sánchez-Olivares and Espín [19]	Authors
Analysis method	First order	Approximate 2nd order - TCIM
External columns (1)	HEB180	IPE200
Internal columns (2)	HEB140	IPE180
Roof beams (3)	IPE 180	IPE180
Floor beams (4)	IPE 240	IPE270
Total weight (Difference)	2250.3 kg	1924.9 kg (-16.9%)

In order to assess the convergence rate of the module developed, the optimization of this frame was made 50 consecutive times, the module returned the optimum result 48 times, or 96% of times. It shows that the stop criteria is enough to this case.

The result shows that the precision gained when using a second order method, even being an approximation, generated a more economical result compared to the first order method, both according to EN 1993-1-1 [10].

The **Erro! Fonte de referência não encontrada.** shows the ratios between values obtained in the analysis by the limit values for the constraints related to the ULS of the most requested elements, calculated according to eq. 3.

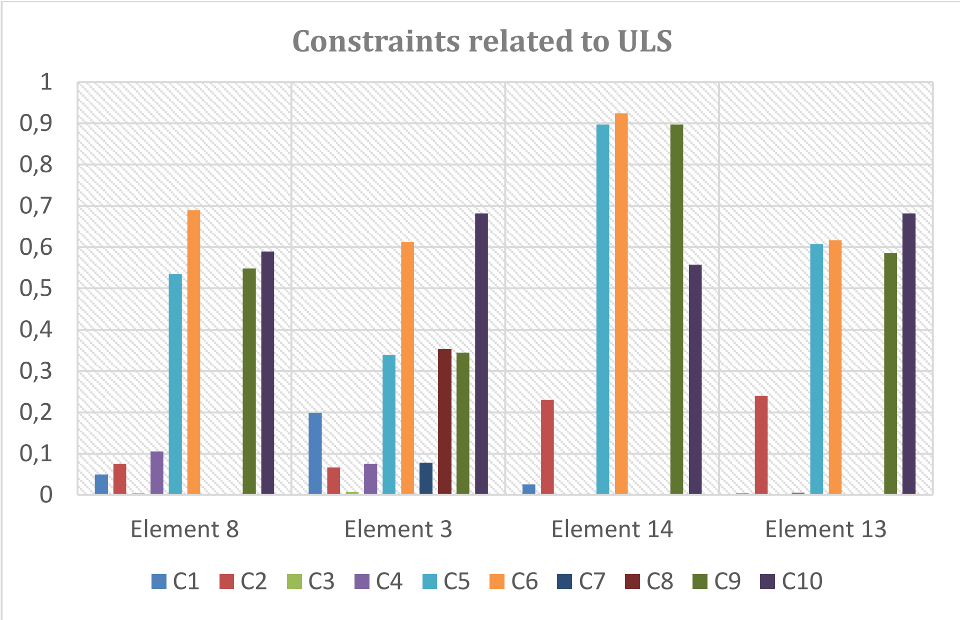

Figure 3. Ratio between values obtained in the analysis by the limit values for ULS according to eq. 3.

The Figure 4 shows the ratios between values obtained in the analysis by the limit values for the constraints related to the SLS of the most requested elements, calculated according to eq. 4.

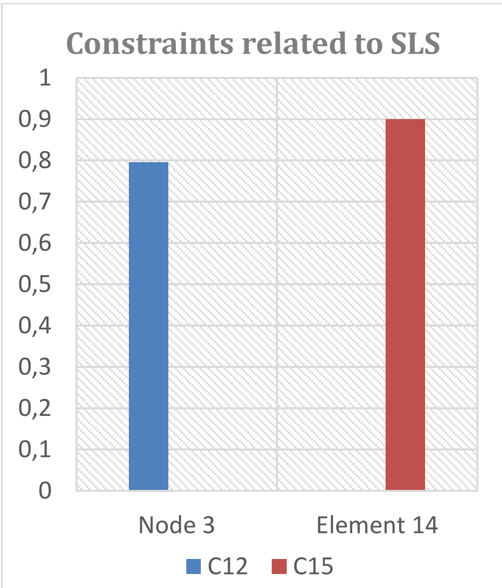

Figure 4. Ratio between values obtained in the analysis by the limit values for SLS according to eq. 4.

The criterion that most influenced the external columns, represented by element 8, was the combination of efforts, represented by the expression C_6 in Eq.3. As for the internal columns, represented by element 3, the governing criterion was the shapes without stiffeners, represented by the expression C_{10} in Eq.3.

For the roof beams, represented by element 14, the factor that exerted the greatest influence was the combination of efforts, represented by the expression C_6 in Eq.3. On the other hand, for the floor beams, represented by element 13, the governing criterion was the shapes without stiffeners, represented by the expression C_{10} in Eq.3

The SLS for maximum deflection of beams, represented by C_{15} in Eq. 4, also influenced the design.

4 Conclusion

The result presented for the steel frame analyzed is consistent with the example from the literature, showing better results. This demonstrates the successful implementation of the approximate second order analysis method in the S3D software. The lighter structure found can be explained by the adoption of a more precise analysis method, since the EN 1993-1-1 [10] prescribes higher safety factors for a first order analysis, because it is less accurate when compared to an approximated second order analysis.

In a general way, the module developed allows us to realize that the GA is efficient in the optimization of steel structures because it works efficiently with tabulated values. Simplified methods, in addition to facilitate implementation without relevant increase of computational demand, also presents accurate results.

Finally, the module developed is a useful tool, which allows the designer to have a clear view of the influence of each parameter on the structural design, both for Ultimate Limit States and for Service Limit States.

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