Optimum design of steel columns filled with concrete via genetic algorithm: environmental impact and cost analysis

Abstract

The use of concrete-filled tubular columns as part of structural systems has steadily increased throughout the years. The growing demand for structural elements of this nature is a direct result of the possibility to use various cross-section shapes that have increased strength, along with resistance to fire and other corrosive agents. The main objective of this article is to present the formulation for optimizing the design of composite columns in accordance with prescriptions from ABNT NBR 16239:2013, considering financial cost and CO$_2$ emission during manufacturing as objective functions. A Genetic Algorithm was used to solve three examples of composite tubular columns subjected to combined bending and compression, considering major axis and unsymmetrical bending. The financial cost in Brazilian currency and the CO$_2$ emission in kilograms attributed to manufacturing concrete-filled composite columns were calculated and the optimization procedure was implemented on composite columns featuring CHS, RHS and SHS steel members. This study also considers the different concrete strengths and the optional inclusion of longitudinal rebar. For the cases analyzed, the financially and environmentally optimum design corresponds to a CHS composite column with no longitudinal rebar and the highest concrete strength tested, except when unsymmetrical bending is applied, in which case the optimum solution includes longitudinal rebar. Furthermore, results indicate that structural steel has the highest impact on the CO$_2$ emission of the optimal designs. For the column with longitudinal rebar, the reinforcement steel presents the second highest financial impact, while concrete is responsible for the highest influence on CO$_2$ emission.

Keywords: steel columns filled with concrete; optimization; cost analysis; CO$_2$ emission; genetic algorithm.

1. Introduction

Tubular steel profiles filled with concrete and subjected to compression are commonly named composite filled columns. The combined use of steel and concrete in structural elements is widely used in civil construction due to advantages such as increased bearing capacity, protection against fire and corrosion and the reduction or exclusion of wooden formwork during construction.

Composite filled columns usually feature steel profiles with rectangular (RHS), square (SHS) or circular (CHS) hollow sections as outer casing and longitudinal rebar in some cases. Guidelines for the design of steel-concrete composite structures are included in the most relevant international design standards. In Brazil, said guidelines are prescribed by ABNT NBR 8800:2008 and ABNT NBR 16239:2013 and the latter presents...
a more specific approach for the design of composite sections featuring tubular profiles. The principal difference between these standards is the adoption of distinct curves for compression and interaction between compression and bending.

Choosing a financially and environmentally optimum cross-section for composite filled columns may be challenging, since numerous section shapes are available for tubular profiles, as well as different possible grades of concrete and rebar configurations. As such, the final decision inevitably requires an optimization analysis, automated or otherwise.

The financial cost of a composite filled column depends on the price of concrete, which varies with its compressive strength, in addition to the prices of the tubular profile and longitudinal rebars. Additionally, CO\textsubscript{2} emission is accounted for during extraction, production and transportation of the raw materials used for manufacturing each component of the structural element, and during the actual manufacturing of the components. Other financial and environmental costs are related to structural connections, architectural aspects, and labor. However, the present study disregards their influence, in similar fashion to the studies conducted by Santoro and Kripka (2020), and Tormen et al. (2020).

The optimum cross-section of a composite filled column may be obtained by coding optimization techniques into a computer program. The program then performs iterative processes that update the values of design variables based on user-defined parameters until the best possible solution is reached. These solutions must also meet structural safety and stability criteria prescribed by pertinent design standards.

2. Genetic algorithm method

The Genetic Algorithm method (GA) was introduced by John Holland in 1960, based on principles of Darwin’s theory of evolution (Holland, 1992). The algorithm seeks to choose the best individuals within a previously defined population from a fitness function. With the determination of the best individuals, a new population will be determined from the determination of the best individuals, population from a fitness function. With individuals within a previously defined theory of evolution (Holland, 1992).

Qiao et al. (2019) analyzed the effect of two variables, spacing between steel bars and concrete strength for square composite columns filled with reinforced concrete and subjected to axial compression. The study is based on the European standard EN 1994-1-1:2004 and the American ANSI / AISC 360-05 associated to ACI 318:1989, which present the theoretical basis for the two optimization models proposed herein. The authors observed that the final resistance to compression is greater when the steel bars are tightly arranged and there is only a small difference between results for each calculation model.

Han et al. (2001) in a series of twenty tests with steel columns filled with concrete, defined a set of parameters, among them, resistance to concrete compression and load eccentricity, for the elaboration of a mechanical model. The results obtained with the mechanical model ensured that the estimates for the capacity and modulus of the studied section agreed reasonably with those obtained with the LRFD method (AISC 1994) and Eurocode 4 part 1 (1996).

In the same way as Qiao et al. (2019), the similarity between the design codes was verified, with the most conservative results obtained via LRFD (AISC 1994).

Papavasileiou et al. (2013) investigated the cost-benefit ratio of concrete encased composite columns and composite filled columns as an alternative for the use of steel I-beam columns. A comparison between column types was performed using structural optimization, seeking to minimize financial costs and safety restrictions imposed by EN 1993-1-1:2005 and EN 1994-1-1:2004. Optimized results favor the use of composite elements in structural systems that require an increased number of columns. The authors also indicate that fire-resistance is amplified when composite columns are used.

Yan et al. (2019) used Abaqus to perform parametric studies on composite square columns filled with reinforced concrete, subjected to axial compression. Numerical results were compared with guidelines from EN 1994-1-1:2004 and presented acceptable agreement, validating the method for calculating the ultimate resistance of the composite columns analyzed.

An ever-increasing demand for sustainable processes in civil construction implies that the search for optimal structural designs cannot be limited to technical and financial factors. Environmental impacts attributed to the production and assembly of structural systems must also be accounted for. Tormen et al. (2020), along with Santoro and Kripka (2020) reinforce this idea by stating that structural optimization procedures should not have the financial cost as the only decisive factor; environmental impacts related to the life cycle of materials and CO\textsubscript{2} emissions should also be considered.

This article presents a formulation for the optimized design of composite filled columns, choosing financial cost and CO\textsubscript{2} emission during production as objective functions. A computational routine featuring a graphic user interface (GUI) was developed with Matlab\textsuperscript{®} (2016), based on the genetic algorithm native to the program’s optimization toolbox and design prescriptions from ABNT NBR 16239:2013. Results obtained with the program allowed the authors to define optimal solutions for the design of composite filled columns, in relation to minimum financial and environmental costs associated with the manufacturing process.
with code specifications.

Artar (2016) minimized the weight of different trusses in accordance with guidelines from the American Institute of Steel Construction (AISC) via GA. Results obtained from the evaluation of three trussed structures were similar to those observed in literature and were able to provide more economical solutions in some cases.

Kripakaran et al. (2011) implemented a computational system for designing steel structures considering cost minimization when connections are included in the model analyzed. Compensation curves based on the ratio between the costs of connections and structural steel were developed and applied to an existing structural model that was later subjected to validation. Results indicate that the design reaches minimum cost when rigid connections are modelled in specific locations.

Kociecki and Adeli (2015) performed optimization of steel framed structures via GA. The study features a simultaneous optimization of topology and shape of roof structures. Results indicate the possibility of assuming free forms for the geometry of the steel structures, which significantly increases the complexity of the study. After analyzing two free-form roof structures of large proportions, the authors reported an efficiency of 10% in both examples, given the methods used for changing the geometry of the structure.

Nobahari et al. (2017) used GA to identify which members of a truss are susceptible to more damage, as well as the extent of the damage that occur in these members. Implementation was exemplified by three numerical models, first identifying the location of the damage, followed by its severity in each member using a limited calculation volume.

Malveiro et al. (2018), used GA to analyze a steel-concrete railway viaduct with experimental data in two phases: first the physical properties were calibrated via GA, followed by the modification of the horizontal stiffness of supports and damping coefficients based on the dynamic response of the decks.

Prendes-Gero et al. (2018), in turn, used GA for optimizing the design of steel framed structures considering three design codes: Spanish, European and American. After assessing the influence of each parameter on the optimized results, the authors determined that the heaviest and lightest designs resulted from using the American and European codes, respectively.

Choudhary and Jana (2018) applied GA in a study to maximize the critical buckling load inside a rectangular orthotropic plate with openings. The authors determined that the positions of the openings depend on material properties, configuration of the laminated plate and its geometry. The importance of GA for determining the position of the openings was evidenced by their role in redistributing stresses on the plane of the orthotropic plate, consequently interfering in the value of the buckling load.

Breda, Pietralonga and Alves (2020) proposed the optimization of variables related to the design of composite steel deck slabs. GA was used to determine the optimum number of secondary beams, as well as the most cost-effective slab design.

Zhu et al. (2020) applied GA to define the optimum mechanical properties of continuous beams subjected to different load combinations. Even with the large number of restrictions present in the design of this type of structure, GA was able to provide optimum solutions in a smooth manner.

Alves and Ramos (2021) presented the optimization of steel-concrete composite cellular beams, comparing failure modes. The study used GA to evaluate which failure modes govern the design of cellular beams and a finite element analysis was used to validate results.

3. Environmental impact

With the objective of reducing the environmental impacts of civil construction, several methodologies have been developed to quantify said impacts. Among the most prominent approaches, the Life-Cycle Evaluation (LCE) is a complex multi-parametric analysis of the entire life-cycle of a structural system, encompassing extraction and production of materials, structural assembly, usage and maintenance, up until the end of the structure’s lifespan. This approach includes some essential aspects concerning environmental impacts, such as CO$_2$ emissions, water and electricity consumption, and the production of waste.

Increased CO$_2$ emission bears negative effects on the global warming phenomenon, and numerous researchers state that the production of this gas is significant during the manufacturing of construction materials. As such, this is one of the most relevant parameters for analyses focused on minimizing environmental impacts arising from civil construction (Payázaforetza et al. (2009), Yepes et al. (2012)).

As shown by Hájek et al. (2011), the use of environmentally optimized reinforced concrete (RC) structures has the potential of increasing the quality of the structural system while also contributing to the sustainable development agenda.

Park et al. (2013) presented a technique for optimizing RC columns that simultaneously consider financial cost and CO$_2$ emissions during the structural design phase. The technique was applied to a 35-story building to assess its effectiveness and reports show that CO$_2$ emissions attributed to concrete are directly proportional to its compressive strength. Although results from this research show that the financial cost and CO$_2$ emissions per unit are larger in high strength materials than in conventional ones, the use of high strength materials effectively reduces overall cost and CO$_2$ emissions. This is a result of a reduction in the volume of components because they present increased strength.

According to Du et al. (2019), one way to achieve sustainable construction is to reduce concrete consumption by using more sustainable, stronger concrete mixes.

The studies performed by Santoro and Kripka (2020) focused on minimizing environmental impacts by optimizing the design of RC elements. The authors observed that RC beams using conventional concrete present lower financial and environmental costs, meaning that cross-section reductions as a result of using high-strength concrete may not be enough to compensate for the added financial expenditure and CO$_2$ emission. RC columns, however, exhibit opposite behavior, with overall financial and environmental costs being inversely proportional to concrete strength.

Tormen et al. (2020) proposed a mathematical model for optimizing the design of steel-concrete composite beams using the harmonic search method, with the objective of reducing financial costs and environmental impacts. Results show that financial optimization leads to more rational material consumption, which is directly related to the reduction of environmental impacts.
4. Mathematical modelling

The optimization procedure is focused on allowing the program to arrive at a solution corresponding to minimum values of financial cost and CO₂ emission functions. The financial cost function, in reais (R$), is shown in Eq. (1) and includes the costs of concrete, steel profile and rebar:

\[
\text{Min Cost} = C_c A_c L + C_a A_a L \rho_a + C_s A_s L \rho_s \quad (1)
\]

where \( C_c \) is the cost per unit-volume of concrete (R$/m³), \( A_c \) is the cross-sectional area of concrete (m²), \( C_a \) is the cost per unit-weight of profiled steel, (R$/kg), \( A_a \) is the cross-sectional area of the steel profile (m²), \( \rho_a \) is the specific mass of the profiled steel (kg/m³), \( C_s \) is the cost per unit-weight of rebar (R$/kg), \( A_s \) is the area of rebar (m²), \( \rho_s \) is the specific mass of rebar steel (kg/m³) and \( L \) is the length of the column (m).

The function for determining CO₂ emissions, in kilograms (kg), is given by Eq. (2) and accounts for emissions attributed to concrete, steel profiles and rebar.

\[
\text{Min CO}_2 \text{ Emission} = \text{CO}_2c A_c L + \text{CO}_2a A_a L \rho_a + \text{CO}_2s A_s L \rho_s \quad (2)
\]

where, \( \text{CO}_2c \), \( \text{CO}_2a \), and \( \text{CO}_2s \) are the emissions attributed to concrete, steel profile and rebar, respectively, all in kgCO₂/kg. Remaining variables are analogous to Eq. (1). To determine the minimum value of functions, the GA native to the Optimization Toolbox™ embedded in Matlab® R2016a was used.

4.1 GA parameters native to Matlab software

A structural optimization procedure was developed using the GA native to Matlab. The solution of problems using this GA specifically is performed in a few steps. First, a random initial population is created, and every individual of the sample is evaluated based on a measured value, also known as aptitude value. From this first population, several individuals will be selected based on their aptitude, forming an elite of individuals that will be kept as part of the next population. Sequentially, a new population will be created by means of crossing or mutation.

In Matlab, GA is interrupted when one of the following stop criteria is reached: number of generations is equal to 100 times the number of variables, a set time limit or an optimum value is reached. For the objective function and calculation of restraints, the precision of the output is \( 10^{-6} \) and \( 10^{-3} \), respectively. The initial population contains 200 individuals, with an elite rate of 0.05 and a crossing rate of 0.85.

4.2 Design variables

The design variables of the program are defined as a function of steel profile geometry, strength of concrete and the rebar, if present (Figure 1). The group of parameters corresponding to the design variables are indicated in Table 1, based on the tubular cross-sections.

![Figure 1 - Set of parameters of the steel profile that make up the design variables.](image)

| Variable            | Rectangular Section | Square Section | Circular Section |
|---------------------|---------------------|----------------|-----------------|
| Width               | \( x_1 = b \)       | \( x_1 = b = h \) | -               |
| Height              | \( x_2 = h \)       | \( x_2 = b = h \) | -               |
| Diameter            | -                   | -              | \( x_3 = b = h \) |
| Thickness           | \( x_3 = t \)       | \( x_3 = t \)  | \( x_3 = t \) |
| Steel Area          | \( x_4 = A_a \)     | \( x_4 = A_a \) | \( x_4 = A_a \) |
| Moment of inertia x axis | \( x_5 = I_{ax} \) | \( x_5 = I_{ax} \) | \( x_5 = I_{ax} \) |
| Moment of inertia y axis | \( x_6 = I_{ay} \) | \( x_6 = I_{ay} \) | \( x_6 = I_{ay} \) |
| Plastic section modulus x axis | \( x_7 = Z_{ax} \) | \( x_7 = Z_{ax} \) | \( x_7 = Z_{ax} \) |
| Plastic section modulus y axis | \( x_8 = Z_{ay} \) | \( x_8 = Z_{ay} \) | \( x_8 = Z_{ay} \) |
The diameter of the steel rebars and the characteristic compressive strength of concrete at 28 days \( (f_c) \) were also considered as design variables.

### 4.3 Constraint functions

The constraint functions of the optimization problem are based on guidelines from the Brazilian standard ABNT NBR 16239:2013. In Eqs. (3)-(17) presented in Table 2, \( N_{s,d} \) is the design value of the resistance to compression, \( N_{w,d} \) is the design compressive load, \( M_{x,d} \) is the design bending strength and \( M_{y,d} \) is the design bending moment. The subscripts \( x \) and \( y \) refer to the principal axes of the cross section with the major and minor inertia, respectively.

| Condition Analyzed                                      | Equation                                      |
|---------------------------------------------------------|-----------------------------------------------|
| Pure Compression                                        | \( N_{w,d} \geq N_{s,d} \)                    |
| Bending and compression                                 | \( N_{w,d} \leq N_{s,d} \) + \( \frac{M_{x,s}}{M_{x,d}} + \frac{M_{y,s}}{M_{y,d}} \leq 1.0 \) (4) |
| Applicability limit for rectangular and square tubular sections | \( \frac{x_1}{x_5} \leq 2.26 \sqrt{\frac{E_s}{f_y}} \) (6) |
| Applicability limit for square tubular section          | \( \frac{x_1}{x_5} \leq 2.26 \sqrt{\frac{E_s}{f_y}} \) (7) |
| Applicability limit for circular tubular section        | \( \frac{X_1}{X_5} \leq 0.15 \sqrt{\frac{E_s}{f_y}} \) (8) |
| Contributing factor of steel                            | \( 0.2 \leq \delta = \frac{A_s f_y}{N_{s,d}} \leq 0.9 \) (9) |
| Number of bars for rectangular and squares sections     | \( n_b \geq 4 \) (10) |
| Number of bars for circular section                     | \( n_b \geq 6 \) (11) |
| Minimum and maximum reinforcement bars                  | \( m_d x \leq \left( 0.004 A_s ; 0.15 \frac{N_{s,d}}{f_y} \right) \leq A_s \leq 0.04 A_s \) (12) |
| Minimum and maximum rebar spacing in each direction for rectangular and square sections | \( S_x = \frac{x_1 - 2x_5 - 2d' - n_b \phi_y}{n_b - 1} \) (13) |
| Minimum and maximum rebar spacing for circular sections | \( S_y = \frac{x_1 - 2x_5 - 2d' - n_b \phi_y}{n_b - 1} \) (14) |
| Maximum (2cm/ph) \( s \) \( \leq s \leq 40 \) cm         | \( s = \frac{2 \pi \left( x_1 - x_5 - d' - \frac{\phi_y}{2} \right)}{n_b} \) (16) |

To allow comparison of results, specific parameters were kept constant. All columns analyzed have uniform cross-sections with end nodes laterally restrained. Local second order effects are included by using the coefficient \( B_1 \) from ABNT NBR 8800:2008, Eq. (18). All columns have a length of 3 m.

\[
B_1 = \frac{C_m}{1 - N_{s,d} / N_{s,eff}}
\]  

\[
C_m = 0.6 + 0.4r
\]  

where \( N_{s,eff} \) is the elastic critical load of a composite column corresponding to a given effective flexural stiffness, \( r \) is the ratio between end moments and \( C_m \) is the moment equivalence coefficient. For the definition of concrete properties, granite/gneiss coarse aggregate was considered in its composition and the modulus of elasticity for
4.4 Search spectrum

For the steel profile, the search spectrum is defined as the available cross-section shapes in a structural steel profile catalogue from the European company Tata Steel (2017). Commercially available diameters were used for the longitudinal rebar. As such, the search spectrum for this component is comprised of available diameters ranging from 5 mm to 40 mm. The possible values for the characteristic compressive strength of concrete $f_{ck}$ are taken as every 5 MPa increment from 20 MPa to 50 MPa. The lower and upper limits chosen for this interval are in accordance with minimum and maximum strength values allowed for structural concrete of conventional strength prescribed by the design standards used for this research.

4.5 Estimation of financial cost and CO$_2$ emission

An estimate of the monetary cost, in Brazilian currency, of every component of the composite column is shown in Table 3. Data concerning the costs of concrete and rebar were collected from Sinapi (2020).

It is important to note that the cost per cubic meter of concrete shown is for pumped industrial concrete with pumping services included, which varies with the strength of concrete. The costs of the steel profiles were obtained by consulting a Brazilian manufacturer and they vary with the cross-section of the tubular element.

Values for kilogram of CO$_2$ emitted per cubic meter of concrete were obtained from Santoro and Kripka (2020). For the steel profile and rebar, emissions were extracted from the LCI Data for Steel Products, based on the Worldsteel Association (2020), considering a recycling rate of 85%. These values are also shown in Table 3.

| Material                        | Costs   | CO$_2$ emissions |
|---------------------------------|---------|-----------------|
| Concrete – 20 MPa               | R$ 295.00/m$³ | 140.05 kgCO$_2$/m$³$ |
| Concrete – 25 MPa               | R$ 307.42/m$³ | 149.26 kgCO$_2$/m$³$ |
| Concrete – 30 MPa               | R$ 317.77/m$³ | 157.65 kgCO$_2$/m$³$ |
| Concrete – 35 MPa               | R$ 329.15/m$³ | 171.74 kgCO$_2$/m$³$ |
| Concrete – 40 MPa               | R$ 341.57/m$³ | 182.14 kgCO$_2$/m$³$ |
| Concrete – 45 MPa               | R$ 384.01/m$³ | 194.70 kgCO$_2$/m$³$ |
| Concrete – 50 MPa               | R$ 455.43/m$³ | 225.78 kgCO$_2$/m$³$ |
| Steel Reinforcement             | R$ 5.01/kg  | 1.204 kgCO$_2$/kg |
| Circular hollow section         | R$ 4.50/kg  | 1.185 kgCO$_2$/kg |
| Square and Rectangular hollow section | R$ 5.50/kg | 1.185 kgCO$_2$/kg |

5. Results and discussions

Three cases with different load configurations were analyzed. These include combined compression and bending about the major axis of inertia and combined compression and bending about both principal axes (Figure 2). For each load case, columns with CHS, RHS and SHS profiles were optimized.

![Figure 2](image-url)
5.1 Example 1 – Combined compression and uniaxial bending

This example represents situations in which normal stresses resulting from axial compression are increased due to the presence of bending. As such, column models were subjected to a 2700 kN compressive force in combination with end moments of 30 kN.m.

Table 4 indicates that, in general, composite columns without rebar present lower CO$_2$ emissions. The relationship between production cost and CO$_2$ emission for this case shows that the most financially and environmentally efficient solution corresponds to the circular composite column without rebar. Alternatively, the best results for longitudinally reinforced columns are obtained with a circular profile.

In the composition of costs and CO$_2$ emission shown in Figure 4, the steel profile is the component with the greatest impact on all columns, both for cost and for CO$_2$ emissions. In composite columns with reinforcement, most cases indicate that the reinforcement has second greatest impact on cost. However, concrete had a greater influence in CO$_2$ emissions in these columns.

| Reinforcement | D (mm) | t (mm) | $f_{c,k}$ (MPa) | n | $d$ (mm) | $A_s$ (cm$^2$) | Cost (R$) | Total CO$_2$ Emissions (kg) |
|---------------|--------|--------|----------------|---|----------|--------------|-----------|---------------------------|
| Circular Composite Column | Without Reinforcement | 273.0 | 5.0 | 50 | - | - | 520.38 | 154.28 |
| With Reinforcement | 273.0 | 5.0 | 40 | 8 | 12.5 | 9.82 | 617.65 | 175.00 |
| Rectangular Composite Column | Without Reinforcement | 200:300 | 5.6 | 45 | - | - | 767.40 | 184.63 |
| With Reinforcement | 200:300 | 5.6 | 30 | 12 | 10.0 | 9.42 | 867.77 | 205.29 |
| Square Composite Column | Without Reinforcement | 250.0 | 6.0 | 40 | - | - | 804.08 | 194.37 |
| With Reinforcement | 250.0 | 6.0 | 30 | 12 | 10.0 | 9.42 | 911.23 | 216.93 |

From financial and environmental standpoints, the optimum solution for this example is obtained by using the design procedure from ABNT NBR 16239:2013 in circular columns with no longitudinal reinforcement. An estimated cost of R$520,38 is obtained with this approach, with a CO$_2$ emission of 154.28 kg. Results for all columns tested in this example are shown in Figure 3, taking the optimum solution as a reference value.
5.2 Example 2 – Combined compression and uniaxial bending

The second example consists of combined bending and compression. An axial load of 3000 kN was applied to the column models. A bending moment of 270 kN.m was applied upon the major principal axis of inertia. Results for columns with circular, rectangular, and square cross-sections are presented in Table 5.

The most financially and environmentally efficient designs for columns with no rebar in this example were obtained using the procedure from ABNT NBR 16239:2013, for circular profiles. If longitudinal rebar is included, the design corresponding to the best solution is the same as in columns with no reinforcement, namely the circular profile. Following a trend from previous examples, these solutions are observed in columns featuring concrete with higher compressive strengths.

Table 5 - Optimization results for combined bending and compression: $N_{Ed}=3000$ kN; $M_{x,Ed}=270$ kN.m.

| Reinforcement | D (mm) | t (mm) | $f_{ck}$ (MPa) | n | $d$ (mm) | $A_s$ (cm²) | Cost (R$) | Total CO$_2$ Emissions (kg) |
|---------------|--------|--------|----------------|---|----------|-------------|-----------|---------------------------|
| Circular Composite Column Without Reinforcement | 355.6  | 6.3    | 50             | - | -        | -           | 858.53    | 255.52                    |
| Circular Composite Column With Reinforcement | 355.6  | 6.3    | 40             | 9 | 12.5     | 11.04       | 957.28    | 274.74                    |
| Rectangular Composite Column Without Reinforcement | 250:350| 7.1    | 50             | - | -        | -           | 1178.00   | 285.77                    |
| Rectangular Composite Column With Reinforcement | 250:350| 6.3    | 50             | 6 | 16.0     | 12.06       | 1205.03   | 295.00                    |
| Square Composite Column Without Reinforcement | 350.0  | 6.0    | 35             | - | -        | -           | 1169.70   | 289.26                    |
| Square Composite Column With Reinforcement | 350.0  | 6.0    | 30             | 6 | 16.0     | 12.06       | 1308.14   | 318.64                    |

The individual performance of each cross-section is compared with the optimal solution in Figure 5, focusing on the percentual difference in relation to the most efficient design. The best solution for this example was found by applying procedures from ABNT NBR 16239:2013 to the design of circular columns without steel reinforcement. This solution corresponds to a production cost of R$858.53 and 255.52 kg of CO$_2$ emission.

Figure 5 shows the CO$_2$ composition for the different solutions obtained.

5.3 Example 3 – Combined compression and biaxial bending

The last example analyzed consists of columns subjected to a combination of compression and bending about both principal axes of inertia. A compressive load with magnitude of 1500 kN, along with 27 kN.m moments in the x and y directions were applied. Results are shown in Table 6.
For columns with no longitudinal reinforcement, the solution corresponding to the lowest financial cost and CO\textsubscript{2} emission is the circular profile. This is also the case for columns with longitudinal rebar. Once more, the best solutions for each cross-section are associated with higher compressive strengths of the concrete.

The results show the overall optimum solution and indicate designs with higher production costs and CO\textsubscript{2} emissions than the most favorable case, as shown in Figure 7.

Table 6 - Optimization results for combined compression and biaxial bending: \( N_{Ed} = 1500 \text{ kN} \); \( M_{x,Ed} = 27 \text{ kN.m} \); \( M_{y,Ed} = 27 \text{ kN.m} \).

| Reinforcement | D (mm) | t (mm) | \( f_k \) (MPa) | n | \( \phi \) (mm) | \( A_s \) (cm\textsuperscript{2}) | Cost (R$) | Total CO\textsubscript{2} Emissions (kg) |
|---------------|--------|--------|----------------|---|--------------|----------------|----------|-------------------------------|
| **Circular Composite Column** | | | | | | | | |
| Without Reinforcement | 244.5 | 5.0 | 35 | - | - | - | 441.11 | 127.24 |
| With Reinforcement | 219.1 | 4.5 | 50 | 7 | 10.0 | 5.50 | 433.34 | 123.74 |
| **Rectangular Composite Column** | | | | | | | | |
| Without Reinforcement | 150:250 | 6.3 | 45 | - | - | - | 664.44 | 155.27 |
| With Reinforcement | 150:250 | 5.0 | 50 | 6 | 12.5 | 7.36 | 634.01 | 152.47 |
| **Square Composite Column** | | | | | | | | |
| Without Reinforcement | 200.0 | 5.0 | 50 | - | - | - | 546.67 | 133.29 |
| With Reinforcement | 200.0 | 5.0 | 40 | 8 | 10.0 | 6.28 | 608.48 | 146.38 |

Figure 7 - Comparative analysis for columns with combined compression and biaxial bending: \( N_{sd} = 1500 \text{ kN} \); \( M_{x,sd} = 27 \text{ kN.m} \); \( M_{y,sd} = 27 \text{ kN.m} \): Cost and CO\textsubscript{2} Emissions.

The best solution for this example was found by applying procedures from ABNT NBR 16239:2013 to the design of longitudinally reinforced circular columns. This solution corresponds to a production cost of R$433.34 and 123.74 kg of CO\textsubscript{2} emission.

In similar fashion to previous examples, the steel profile was the component of greatest impact for both the cost and CO\textsubscript{2} emission, as shown in Figure 8. Analogous to Example 1 and Example 2, composite columns with reinforcement present reinforcing steel as the having the second greatest impact on cost, in most cases. Concrete had a greater influence in CO\textsubscript{2} emissions in these columns.

Comparison between solutions from Examples 2 and 3 shows that the largest bending moment results in a 65% increase in production cost and CO\textsubscript{2} emission.

In example 3, as shown by the composition of costs and CO\textsubscript{2} emissions in Figure 8, the steel profile was also the component with the greatest impact, both for cost and for CO\textsubscript{2} emissions. As in Example 2, in composite columns with reinforcement, the element with the second greatest impact on cost, in general, was the reinforcement. In these columns, when it comes to CO\textsubcript{2} emissions, concrete had a greater influence.
6. Conclusions

The main objective of this article was to present a formulation for optimizing the design of composite tubular columns in accordance with NBR 16239:2013, minimizing cost and CO<sub>2</sub> emission during manufacturing. A Genetic Algorithm was used to determine the optimum solution for composite columns undergoing flexo-compression featuring steel CHS, RHS and SHS members, different concrete grades and the optional inclusion of longitudinal reinforcement.

Results showed that the optimum solutions for composite tubular columns usually include a CHS profile, concrete with higher compressive strength and no longitudinal rebar. Except for columns subjected to unsymmetrical bending, in which the optimum solution uses longitudinal reinforcement. The differences between optimal solutions and least favorable alternatives concerning financial and environmental impacts are substantial, showing reductions in production cost and CO<sub>2</sub> emission of up to 48% and 35%, respectively.

For all cases, steel was observed as the most expensive and the least environmentally friendly material, contributing with more than 80% of cost and emissions in columns with no reinforcement and more than 70% otherwise. Also, longitudinally reinforced columns presented reinforcing steel as the second most expensive material, while concrete generated the largest impact on CO<sub>2</sub>.

Based on the cases studied, it is reasonable to conclude that rebar should be used when the bearing capacity of profile and concrete have been surpassed, which is the only case when the use of reinforcement is viable.

The association between optimal solutions and the use of higher strength concrete in all cases studied is also a noteworthy observation. Despite CO<sub>2</sub> emissions during the production of concrete being directly proportional to its compressive strength, the added structural resistance obtained from the combination of concrete and the steel profile leads to more efficient designs.

In closure, the authors conclude that the design optimization of steel-concrete composite filled columns considering financial costs and rational material consumption is directly related to the reduction of environmental impacts. As such, the technique implemented herein for optimizing the design of these structural elements, along with the results obtained, are aligned with the current need for alternatives that promote the development of environmentally sustainable endeavors in the civil construction market.

Acknowledgements

The authors gratefully acknowledge the agencies FAPES (Fundação de Amparo à Pesquisa e Inovação do Espírito Santo), CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brazil) and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil) for providing financial support.

References

ALVES, E. C.; RAMOS, J. R. Numerical analysis of collapse modes in optimized design of alveolar Steel-concrete composite beams via genetic algorithms. REM – International Engineering Journal, v. 74, n. 2, p. 173-181, 2021. DOI: http://dx.doi.org/10.1590/0370-44672020740060.

AMERICAN CONCRETE INSTITUTE. ACI 318-89: Building Code requirements for reinforced concrete. Detroit: ACI, 1989.

AMERICAN INSTITUTE OF STEEL CONSTRUCTION. Load and resistance factor design specification for structural steel buildings. Chicago: AISC, 1994.

AMERICAN NATIONAL STANDARDS INSTITUTE. ANSI/AISC 360:05: Specification for steel structural buildings. Washington: ANSI, 2005.

ARTAR, M. A comparative study on optimum design of multi-element truss structures. Steel and Composite Structures, v. 22, n. 3, p. 521-535, 2016. DOI: http://dx.doi.org/10.12989/scs.2016.22.3.521.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ABNT NBR 6118: Projeto de estruturas de concreto - Procedimento. Rio de Janeiro: ABNT, 2014.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ABNT NBR 8800: Projeto de estruturas de aço e de estruturas mistas de aço e concreto de edifícios. Rio de Janeiro: ABNT, 2008.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ABNT NBR 16239: Projeto de estruturas de aço e de estruturas mistas de aço e concreto de edificações com perfis tubulares. Rio de Janeiro: ABNT, 2013.

BREDA, B. D.; PIETRALONGA, T.; ALVES, E. C. Optimization of the structural system with composite beam and composite slab using Genetic Algorithm. IBRACON Structures and Materials Journal, v. 13, n. 6, p. 1-14, 2020. DOI: http://dx.doi.org/10.1590/S1983-41952020000600002.

CHO, H.; MIN, D.; LEE, K. Optimum life-cycle design of orthotropic steel deck bridges. Journal of Korean Society of Steel Construction, v. 13, n. 4, p. 337-349, 2001.

CHOUHDARY, P. K.; JANA, P. Position optimization of circular/elliptical cutout within an orthotropic rectangular plate for maximum buckling load. Steel and Composite Structures, v. 29, n. 1, p. 39-51, 2018. DOI: http://dx.doi.org/10.12989/scs.2018.29.1.039.

DU, Y.; XIONG, M-X.; ZHU, J.; LIEW, J. Y. R. Compressive and flexural behaviors of ultra-high strength
concrete encased steel members. *Steel and Composite Structures*, v. 33, n. 6, p. 849-864, 2019. DOI: http://dx.doi.org/10.12989/scs.2019.33.6.849.

EUROPEAN COMMITTEE FOR STANDARDIZATION. *EN 1993-1-1*: Eurocode 3 – Design of steel structures. Part 1.1: general rules and rules for buildings. Brussels, Belgium: CEN, 2005.

EUROPEAN COMMITTEE FOR STANDARDIZATION. *EN 1994-1-1*: Eurocode 4 – Design of steel and concrete structures. Part 1.1: general rules and rules for buildings. Brussels, Belgium: CEN, 1996.

EUROPEAN COMMITTEE FOR STANDARDIZATION. *EN 1994-1-1*: Eurocode 4 – Design of composite steel and concrete structures. Part 1.1: General rules and rules for buildings. Brussels, Belgium: CEN, 2004.

FU, K. C.; ZHAI, Y.; ZHOU, S. Optimum design of welded steel plate girder bridges using a genetic algorithm with elitism. *Journal of Bridge Engineering*, v. 10, n. 3, p. 291-301, 2005. DOI: https://doi.org/10.1061/(ASCE)1084-0702(2005)10:3(291).

HÁJEK, P.; FIALA, C.; KYNCLOVÁ, M. Life cycle assessments of concrete structures—a step towards environmental savings. *Structure Concrete*, v. 12, n. 1, p. 13-22, 2011. DOI: https://doi.org/10.1002/suco.201000026.

HAN, L.; ZHAO, X.; TAO, Z. Tests and mechanics model for concrete-filled SHS stub columns, columns and beam-columns. *Steel and Composite Structures*, v. 1, n. 1, p. 51-74, 2001. DOI: http://dx.doi.org/10.12989/scs.2001.1.1.051.

HOLLAND, J. H. *Adaptation in natural and artificial systems*: an introductory analysis with applications to biology, control, and artificial intelligence. [S. l.]: Bradford Book, 1992. DOI: https://doi.org/10.7551/mitpress/1090.001.0001.

KOCIECKI, M.; ADELI, H. Shape optimization of free-form steel space-frame roof structures with complex geometries using evolutionary computing. *Engineering Applications of Artificial Intelligence*, v. 38, p. 168–182, 2015. DOI: https://doi.org/10.1016/j.engappai.2014.10.012.

KRIPAKARAN, P.; HALL, B.; GRUPTA, A. A genetic algorithm for design of moment-resisting steel frames. *Structural and Multidisciplinary Optimization*, v. 44, n.4, p. 559-574, 2011. DOI: https://doi.org/10.1007/s00158-011-0654-7.

LIU, C.; HAMMAD, A.; ITOH, Y. Multiobjective optimization of bridge deck rehabilitation using a genetic algorithm. *Computer-aided Civil and Infrastructure Engineering*, v. 12, n.6, p. 431-443, 1997. DOI: https://doi.org/10.1111/0885-9507.00001.

MALVEIRO, J.; RIBEIRO, D.; SOUZA, C.; CALÇADA, R. Model updating of a dynamic model of a composite steel-concrete railway viaduct based on experimental tests. *Engineering Structures*, v. 164, p. 40-52, 2018. DOI: https://doi.org/10.1016/j.engstruct.2018.02.057.

MATHWORKS. MATLAB. Versão R2016a. [S. l.]: MathWorks, 2016.

NOBAHARI, M.; GHASEMI, M. R.; SHABAKHTY, N. Truss structure damage identification using residual force vector and genetic algorithm. *Steel and Composite Structures*, v. 25, n. 4, p. 485-496, 2017. DOI: http://dx.doi.org/10.12989/scs.2017.25.4.485.

PAPAVASILEIOU, G. S.; NICOLAOU, N.; CHARMPIS, D. C. Comparative assessment of buildings with pure steel or steel-concrete composite columns using structural design optimization. In: ECCOMAS Thematic Conference - INTERNATIONAL CONFERENCE ON COMPUTATIONAL METHODS IN STRUCTURAL DYNAMICS AND EARTHQUAKE ENGINEERING, 4., 2013, Greece. *Proceedings […]. [S. l.]: IACM, 2013.*

PARK, H. S.; KWON, B. K.; SHIN, Y. A.; KIM, Y. S.; HONG, T. H.; CHOI, S.W. Cost and CO$_2$ emission optimization of steel reinforced concrete columns in high-rise buildings. *Energies*, v. 6, n. 11, p. 5609-5624, 2013. DOI: https://doi.org/10.3390/en6115609.

PAYÁ-ZAFORTEZA, I.; YEPES, V.; HOSPITALER, A.; GONZÁLEZ-VIDOSA, F. CO$_2$ - optimization of reinforced concrete frames by simulated annealing. *Engineering Structures*, v. 31, n. 7, p. 1501-1508, 2009. DOI: https://doi.org/10.1016/j.engstruct.2009.02.034.

PRENDES-GERO, M. B.; BELLO-GARCÍA, A.; COZ-DÍAZ, J. J.; DOMÍNGUEZ, F. J. S.; GARCÍA NIETO, P.J. Optimization of steel structures with one genetic algorithm according to three international building codes. *Construction Journal*, v. 17, n. 1, p. 47-59, 2018. DOI: http://dx.doi.org/10.7764/rdlc.17.1.47.

QIAO, Q.; ZHANG, W.; MOU, B.; CAO, W. Effect of spiral spacing on axial compressive behavior of square reinforced concrete filled steel tube (RCFST) columns. *Steel and Composite Structures*, v. 31, n. 6, p. 559-573, 2019. DOI: http://dx.doi.org/10.12989/scs.2019.31.6.559.

SANTORO, J. F.; KRIPKA, M. Minimizing environmental impact from optimized sizing of reinforced concrete elements. *Computers and Concrete*, v. 25, n. 2, p. 111-118, 2020. DOI: https://doi.org/10.12989/cac.2020.25.2.111.

SINAPI-ES – Sistema Nacional de Pesquisa de Custos e Índices da Construção Civil/Espírito Santo. Vitória: IBGE: Caixa Econômica Federal, 2020.

TATA STEEL. *Structural tubes circular, square and rectangular section* – Structural Catalog. [S. l.]: Tata Steel, 2017. Available at: https://www.tatasteel.com/products-solutions/europe/#.
TORMEN, A. F.; PRAVIA, Z. M. C.; RAMIRES, F. B.; KRIPKA, M. Optimization of steel concrete composite beams considering cost and environmental impact. *Steel and Composite Structures*, v. 34, n. 3, p. 409-421, 2020. DOI: https://doi.org/10.12989/scs.2020.34.3.409.

YAN, B.; GAN, D.; ZHOU, X.; ZHU, W. Influence of slenderness on axially loaded square tubed steel-reinforced concrete columns. *Steel and Composite Structures*, v. 33, n. 3, p. 375-388, 2019. DOI: http://dx.doi.org/10.12989/scs.2019.33.3.375.

YEPES, V.; GONZÁLEZ-VIDOSA, F.; ALCALÁ, J.; VILLALBA, P. CO$_2$ optimization design of reinforced concrete retaining walls based on a VNS-threshold acceptance strategy. *Journal of Computing in Civil Engineering*, v. 26, n. 3, p. 378-386, 2012. DOI: https://doi.org/10.1061/(ASCE)CP.1943-5487.0000140.

WORLDESTEEL ASSOCIATION. LCI Data for Steel Products. [S. l.]: Worldsteel Association, 2020.

ZHU, E.; NAJEM, R. M.; DINH-CONG, D.; SHAO, Z.; WAKIL, K.; HO, L. S.; ALYousef, R.; ALABDULJABBAR, H.; ALASKAR, A.; ALRSHOUDI, F.; MOHAMED, A. M. Optimizing reinforced concrete beams under different load cases and material mechanical properties using genetic algorithms. *Steel and Composite Structures*, v. 34, n. 4, p. 467-485, 2020. DOI: http://doi.org/10.12989/scs.2020.34.4.467.

Received: 17 May 2021 - Accepted: 20 January 2022.