Civil Engineering
Engenharia Civil

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

http://dx.doi.org/10.1590/0370-44672021750034

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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_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.

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 I (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_2 emissions should also be considered.

This article presents a formulation for the optimized design of composite filled columns, choosing financial cost and CO_2 emission during production as objective functions. A computational routine featuring a graphic user interface (GUI) was developed with Matlab® (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.

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 crossover, mutation operations.

Numerous applications of GA in engineering are observed. Liu *et al.* (1997) implemented GA in a study of bridges aimed at minimizing the total cost and evaluating rehabilitation strategies for the bridges. The research analyzed a total of 287 bridges from a Japanese database, 269 with concrete decks and 18 with steel decks. The level of deterioration and a traffic coefficient were defined based on the width and the length of the structures. GA was proven to be an effective method, planning long-term maintenance.

Cho *et al.* (2001) also implemented GA for bridge optimization, but with the objective of minimizing the life-cycle cost of steel deck bridges, including initial cost, maintenance cost, deflection and fatigue on the structure. By implementing GA, the authors were able to present rational project solutions that were cheaper and safer.

Fu *et al.* (2005) developed a study using GA to minimize the weight and the cost of beam plates welded onto bridges with different geometries. Results showed GA's ability to easily deal with discrete variables, the capability of the method for associating geometric parameters that influenced the configuration of the bridges, such as the distance between beams, and the advantage of defining a real engineering project in accordance 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 lighest 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 (Payá-zaforteza *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 CO_2 emission functions. The financial cost function, in reais (R$), is shown in Eq. (1) and includes the costs of concrete, steel profile and rebar:

$$Min\ Cost = C_c A_c L + C_a A_a L\rho_a + C_s A_s L\rho_s \qquad (1)$$

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), ρ_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), ρ_s is the specific mass of rebar steel (kg/m³) and L is the length of the column (m).

The function for determining CO_2 emissions, in kilograms (kg), is given by Eq. (2) and accounts for emissions attributed to concrete, steel profiles and rebar.

$$Min\ CO_2\ Emission = CO_{2c} A_c L + CO_{2a} A_a L\rho a + CO_{2s} A_s L\rho_s \qquad (2)$$

where, CO_{2c}, CO_{2a} and CO_{2s} are the emissions attributed to concrete, steel profile and rebar, respectively, all in kgCO_2/kg. Remaining variables are analogous to Eq. (1). To determine the minimum value of functions, the GA native to the Optimization ToolboxTM 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.

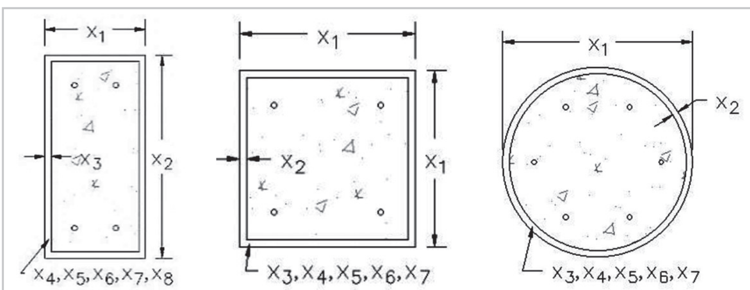

Figure 1 - Set of parameters of the steel profile that make up the design variables.

Table 1 - Design variables for a given tubular cross section.

Variable	Rectangular Section	Square Section	Circular Section
Width	$x_1 = b$	$x_1 = b = h$	-
Height	$x_2 = h$	$x_1 = b = h$	-
Diameter	-	-	$x_1 = b = h$
Thickness	$x_3 = t$	$x_2 = t$	$x_2 = t$
Steel Area	$x_4 = A_a$	$x_3 = A_a$	$x_3 = Aa$
Moment of inertia *x* axis	$x_5 = I_{ax}$	$x_4 = I_{ax}$	$x_4 = I_{ax}$
Moment of inertia *y* axis	$x_6 = I_{ay}$	$x_5 = I_{ay}$	$x_5 = I_{ay}$
Plastic section modulus *x* axis	$x_7 = Z_{ax}$	$x_6 = Z_{ax}$	$x_6 = Z_{ax}$
Plastic section modulus *y* axis	$x_8 = Z_{ay}$	$x_7 = Z_{ay}$	$x_7 = Z_{ay}$

The diameter of the steel rebars and the characteristic compressive strength of concrete at 28 days (f_{ck}) 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_{Rd} is the design value of the resistance to compression, N_{Sd} is the design compressive load, M_{Rd} is the design bending strength and M_{Sd} 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.

Table 2 - Constraint functions from NBR 16239:2013.

Condition Analyzed	Equation	
Pure Compression	$N_{Rd} \geq N_{Sd}$	(3)
Bending and compression	$N_{Sd} \leq N_c \quad \frac{M_{x,Sd}}{M_{x,Rd}} + \frac{M_{y,Sd}}{M_{y,Rd}} \leq 1.0$	(4)
	$N_{Sd} > N_c \quad \frac{N_{Sd} - N_c}{N_{Rd} - N_c} + \frac{M_{x,Sd}}{M_{x,Rd}} + \frac{M_{y,Sd}}{M_{y,Rd}} \leq 1.0$	(5)
Applicability limit for rectangular and square tubular sections	$\frac{x_1}{x_2} \leq 2.26 \sqrt{\frac{E_a}{f_y}} \quad e \quad \frac{x_2}{x_3} \leq 2.26 \sqrt{\frac{E_a}{f_y}}$	(6)
Applicability limit for square tubular section	$\frac{x_1}{x_2} \leq 2.26 \sqrt{\frac{E_a}{f_y}}$	(7)
Applicability limit for circular tubular section	$\frac{X_1}{X_2} \leq 0.15 \frac{E_a}{f_y}$	(8)
Contributing factor of steel	$0.2 \leq \delta = \frac{A_a f_{yd}}{N_{pl,Rd}} < 0.9$	(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	$máx \leq \left(0.004A_c; 0.15 \frac{N_{Sd}}{f_{sd}}\right) \leq A_s \leq 0.04A_c$	(12)
Minimum and maximum rebar spacing in each direction for rectangular and square sections	$S_x = \frac{x_1 - 2x_3 - 2d' - n_{bx}\phi_b}{n_{bx} - 1}$	(13)
	$S_y = \frac{x_1 - 2x_2 - 2d' - n_{by}\phi_b}{n_{by} - 1}$	(14)
	$máx\,(2cm;\phi_b) \leq s_x, s_y$	(15)
Minimum and maximum rebar spacing for circular sections	$s = \frac{2\pi\left(\frac{x_1}{2} - x_2 - d' - \frac{\phi_b}{2}\right) - n_b\phi_b}{n_b}$	(16)
	$máx\,(2\,cm;\phi_b) \leq s \leq 40cm$	(17)

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 B1 from ABNT NBR 8800:2008, Eq. (18). All columns have a length of 3.0 m.

$$B_1 = \frac{C_m}{1 - N_{Sd} / N_{cr,eff}} \tag{18}$$

$$C_m = 0.6 + 0.4r \tag{19}$$

where $N_{cr,eff}$ 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 concrete (E_c) was determined with Eq. (20), according to ABNT NBR 6118:2014.

$$E_c = \alpha_E \cdot 5600\sqrt{f_{ck}} \quad (20)$$

where α_E is a parameter that depends on the nature of the aggregate that influences the modulus of elasticity, equal to 1.0 for granite and gneiss.

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.

Table 3 - Materials cost and CO_2 emissions.

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.

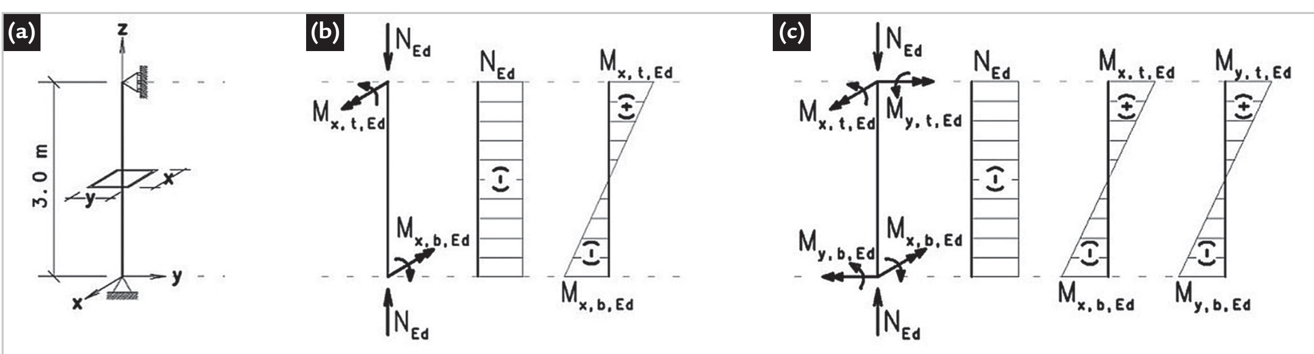

Figure 2 - Three load cases analyzed and the respective forces and bending moments applied on a 3.0 meter long column: (a) Column; (b) Combined Compression and uniaxial bending (Examples 1 and 2); (c) Combined Flexure (x and y axes) and Compression (Example 3).

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.

Table 4 - Optimization results for combined bending and compression: N_{Ed}=2700 kN; $M_{x,Ed}$=30 kN.m.

Reinforcement	D (mm)	t (mm)	f_{ck} (MPa)	n	ϕ (mm)	A_s (cm²)	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.

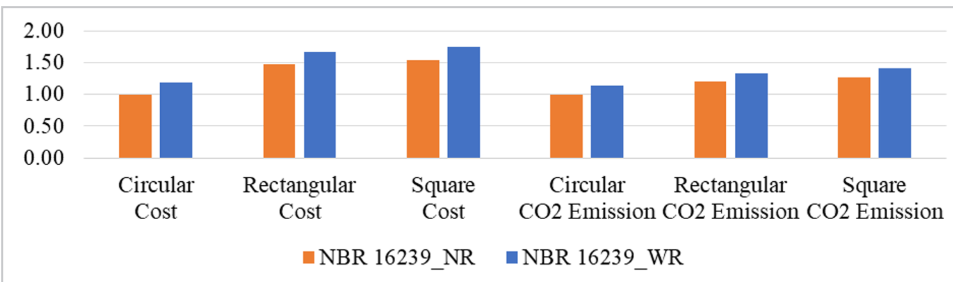

Figure 3 - Comparative analysis for columns with combined bending and compression: N_{Sd}=2700 kN; $M_{x,sd}$=30 kN.m: Cost and CO_2 Emissions.

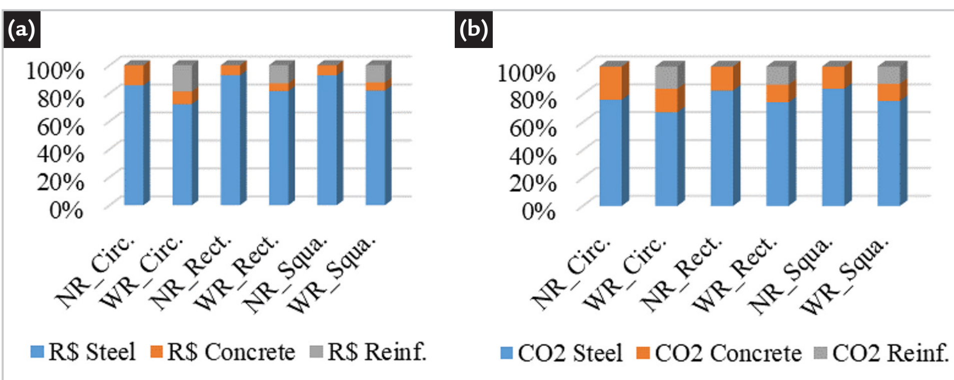

Figure 4 - Composition for composite column subjected to N_{Sd}=2700 kN and $M_{x,sd}$=30 kN.m: (a) Cost Composition; (b) CO_2 Emission Composition.

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	ϕ (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
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
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
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 6 shows the CO_2 composition for the different solutions obtained.

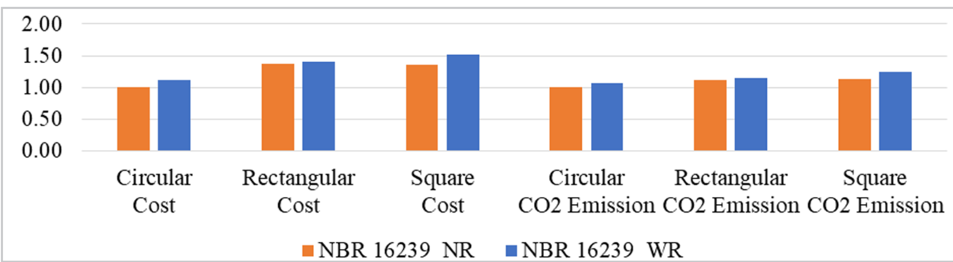

Figure 5 - Comparative analysis for columns with combined bending and compression: N_{Sd}=3000 kN; $M_{x,sd}$=270 kN.m: Cost and CO_2 Emissions.

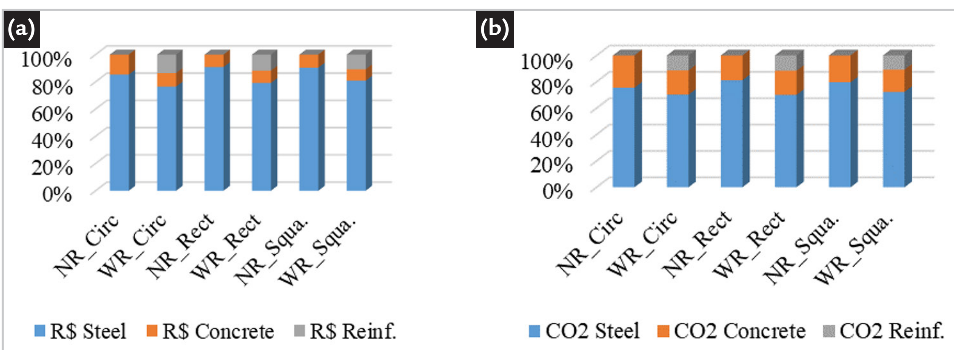

Figure 6 - Composition for composite column subject to N_{Sd}=3000 kN; $M_{x,sd}$=270 kN.m: (a) Cost Composition; (b) CO_2 Emission Composition.

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.

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

Reinforcement	D (mm)	t (mm)	f_{ck} (MPa)	n	ϕ (mm)	A_s (cm²)	Cost (R$)	Total CO_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

For columns with no longitudinal reinforcement, the solution corresponding to the lowest financial cost and CO_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_2 emissions than the most favorable case, as shown in Figure 7.

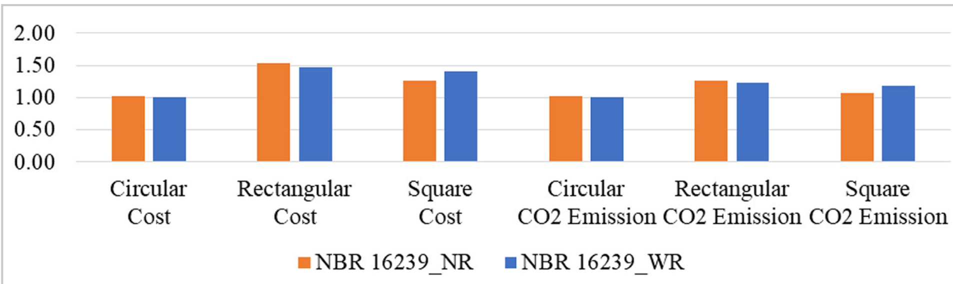

Figure 7 - Comparative analysis for columns with combined compression and biaxial bending: N_{sd}=1500 kN; $M_{x,sd}$=27 kN. m; $M_{y,sd}$=27 kN.m: Cost and CO_2 Emissions.

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_2 emission.

In similar fashion to previous examples, the steel profile was the component of greatest impact for the cost and CO_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_2 emissions in these columns.

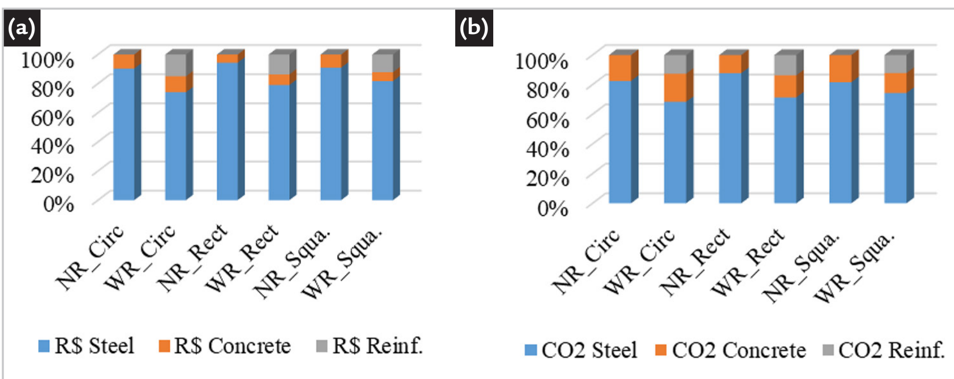

Figure 8 - Composition for composite column subject to N_{sd}=1500 kN; $M_{x,sd}$=27 kN. m; $M_{y,sd}$=27 kN.m: (a) Cost Composition; (b) CO_2 Emission Composition.

Comparison between solutions from Examples 2 and 3 shows that the largest bending moment results in a 65% increase in production cost and CO_2 emission.

In example 3, as shown by the composition of costs and CO_2 emissions in Figure 8, the steel profile was also the component with the greatest impact, both for cost and for CO_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_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_2 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 includes 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_2 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_2.

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_2 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.

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