Optimal Design of Composite Cellular Beams with Partial Interaction and its Environmental Impacts

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Abstract. This work aims to present the formulation of the optimization problem of composite cellular beams of steel and concrete considering partial interaction between beam and slab, based on the design restrictions prescribed in specialized literature adapted to the current Brazilian standardization. Genetic algorithms are used to solve the optimization problem by finding the combination of geometry of the steel profile, characteristic strength of the concrete and degree of shear connection that minimize financial cost and CO2 emission. Finally, this methodology is applied to problems mentioned in literature for comparison and validation purposes.

Keywords: Optimization, Composite Beams, Cellular Beams, Partial Interaction, CO2 Emission;

1 Introduction

The development of urban population and technology in recent years has created an increasing demand for the construction of more robust, modern and economical buildings. According to the Global Status Report [1], buildings and construction account for 39% of all carbon emissions in the world, of which 11% are associated with the materials and construction processes throughout the building lifecycle. Thus, given the growing concern with the consequences of the emission of greenhouse gases in the atmosphere, the scientific community has been striving to develop new materials and methods to reduce the impacts of civil construction on the environment.

The use of steel-concrete composite beams has been proving itself to be an efficient technique to exploit the best of both materials, providing an increase on its strength and enabling more economic solutions [2].

Another technique that has been showing great results is the alveolar beams, which consist of steel profiles with opening in its webs. The most common formats are the hexagonal, called castellated, and circular, called cellular, that, according to Eldal et al. [3], are more efficient and economical due to its flexible geometry. These openings provide an increase on the profile's moment of inertia and, consequently, of its bending moment resistance, while also reducing the structure's weight and material consumption. Nseir et al. [4] also states that this resistance gains more than compensates the additional cost generated by the cutting and welding necessary to its fabrication. It can also be mentioned that alveolar beams are capable of overcoming greater spans than non-alveolar profiles and allow the passage of ducts through their openings, contributing to the building's aesthetics.

When both techniques are combined, a considerable increase in the stiffness of the floor is obtained, a reduction of between 20% and 40% in the steel profile's weight and a lower slab thickness [5]. Another aspect worth mentioning is that this type of structure is especially effective for uniformly loaded beams of small and medium intensity [6].

In order to behave as one single element, shear connectors are needed to unite steel profile and slab. According to Classen [7], the interaction between profile and slab is called full when the addition of more connectors does not yield an increase in the element's resistance. On the other hand, the interaction is called partial when the number of connectors used is sufficient to transmit part - but not completely - the efforts between one element and another. The consideration of partial interaction generally leads to more economical solutions, as it allows a significant decrease in the number of connectors, causing a relatively small reduction in the bending resistance when compared to full interaction [8].

Currently, the design of structures has been often done by iterative trial and error [9, 10]. However, with the advancement of technologies and computing, different algorithms have been developed and applied to structural optimization aiming to obtain more economical solutions with less environmental impact [11]. One of these algorithms is the Genetic Algorithm, based on Darwin's theory of natural evolution, which starts from an initial population of solutions to the problem, tests them according to an objective function and creates a new population from the crossing of the best solutions. In each new population, random values, called mutations, are added and the process repeats until there's convergence [12].

Several studies have been done in the last years towards the minimization of environmental impact of various structures, as done by Lubke, Alves and Azevedo [13] for cellular beams, by Breda, Pietralonga and Alves [12] for composite beams and by Ramos and Alves [14] for composite cellular beams. However, there's still a gap regarding the optimization of cellular composite beams considering partial interaction between steel profile and concrete slab. Thus, the present work proposes a program that performs the security verification and optimization, minimizing the CO_2 emission from cellular composite beams, considering partial and full interaction, using genetic algorithms.

2 Formulation and implementation of the optimization problem

The developed program is implemented with the Software Matlab 2016a [15] considering a simply supported composite cellular beam of steel and concrete. The steel profile consists of a doubly symmetric I-section with a circular opening on its web and is attached to a composite slab by stud bolt shear connectors. In order to provide the optimal solution, the software must find the alternative which presents the lowest CO_2 emission between the ones who meets the standardized criteria for ultimate and serviceability limit states.

For that matter, three variables were considered in this study: steel profile (x_1), characteristic strength of the concrete slab (x_2) and degree of shear connection (x_3).

The first variable determines the geometry of the steel profile by searching on a catalog of structural I-shaped profiles, commercialized by Gerdau [16]. Then, its dimensions are defined on the objective function as shown on Fig. 1. x_2 varies between commercial strength values, ranging from 5 to 5 MPa, between 20MPa - the minimum compressive strength prescribed by ABNT NBR 6118:2014 [17] for structural elements - and 90 MPa. As for x_3, it is made a discretization from 0.4, the minimum degree of shear connection, and 1, representing full shear connection, in 0.01 intervals. Also, the position limits of the shear connectors follow the criteria prescribed by ABNT NBR 8800:2008 [18].

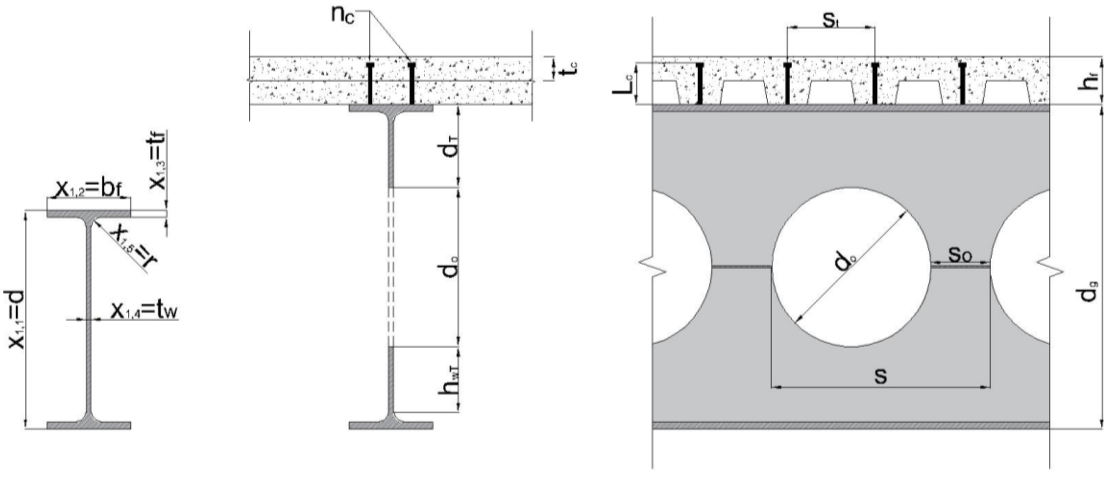

Fig. 1 Geometric variables of the composite cellular beam.

In Fig. 1, x_1 provides the dimensions of the steel profile: $x_{1,1}$ is the depth of the profile (*d*), $x_{1,2}$ is width of the flange (b_f), $x_{1,3}$ the thickness of the flange (t_f), $x_{1,4}$ the thickness of the web (t_w) and $x_{1,5}$ the lamination radius. Fig. 1 also shows the symbols adopted for the length between openings, *s*, the diameter of the alveolus, d_0, whose value corresponds to *2d(k-1)*, where k is the relation between d_g and d. Furthermore, L_c represents the length of the shear connector, t_c the depth of concrete above decking profile and h_t the overall depth of decking profile.
The objective function that minimizes CO2 emission is given by Eq. (1):

$$CO_{2,total} = CO_{2,steel} + CO_{2,concrete} + CO_{2,connector} + CO_{2,cut} + CO_{2,weld} + CO_{2,formwork} \tag{1}$$

where:

$$CO_{2,steel} = E_s \left\{ \left[\left(x_{1,1}\, k - 2x_{1,3} \right) x_{1,4} + 2x_{1,2}x_{1,3} + (4-\pi)x_{1,5}^2 \right] L - \left[\left(\frac{\pi d_0^2}{4} \right) x_{1,4} \left(\frac{L - 2s_e}{s} \right) \right] \right\} \rho_a \tag{2}$$

$$CO_{2,concrete} = E_c b_e\, L\, h_{ef} \tag{3}$$

$$n_{sc} = 2 \cdot \lceil x_3 \frac{F_{hd}}{Q_{Rd}} \rceil \tag{4}$$

$$CO_{2,connector} = E_s n_{sc} A_{cs}\, L_c \rho_a \tag{5}$$

$$CO_{2,cut} = E_{cut} \cdot \left[2 \left(\frac{L - 2s_e}{s} \right) \left(s_O + \frac{\pi d_O}{2} \right) + 2s_e \right] \tag{6}$$

$$CO_{2,weld} = E_w \cdot \left[\left(\frac{L - 2s_e}{s} \right) s_O + 2s_e \right] \tag{7}$$

Where E_s is the emission of CO_2 per unit mass of produced steel; L the length of the beam; s_e the length of the profile without web openings, at the extremities of the beam; ρ_a is the specific mass of steel, taken as 7850kg/m³; E_c the emission of CO_2 per unit volume of concrete with the corresponding characteristic strength; b_e is the effective width of the concrete tee; h_{eq} the equivalent thickness of concrete layer, given by the geometry of the steel formwork; $n_{sc}$is the number of shear connectors on the beam; Q_{Rd} is the shear resistance of a single connector and F_{hd} is the total design shear force for full shear interaction, both of then calculated according to NBR 8800:2008 [18]; E_{cut} is the emission of CO_2 per unit length of the cellular beam during production; and E_w the emission of CO_2 generated by welding processes.

2.1. CO2 Emission of the constituent materials

The average CO_2 of the cellular beam is determined from the unitary mass emission provided by the Sustainability Report [20], but since the total CO2 contribution is not simply given in function of its mass, an additional value is taken into account using a proportion from the results of Rahman et. al. [19] and Chang et. al. [20], as shown in eq. 8 and 9, to considerate the contribution of the profile cutting and welding.

$$E_{cut} = \frac{43.8}{4.9} \times \frac{t_w}{12} \tag{8}$$

$$E_w = 3.3 \times \frac{A_{wl}}{158} \tag{9}$$

The emission per volume of concrete for various values of characteristic strength was determined applying the unitary values of emission per mass of each of its constituent raw materials, given by Santoro and Kripka [21], to the experimental proportions presented by Barboza and Bastos [22] and Thomaz [23]. The unitary emission f the connectors are determined in function of its steel mass and the steel deck emission is extracted from Worldsteel Association [24].

Table 1. Cost of constituent materials.

Material	CO_2 Emission	Material	CO_2 Emission
Cellular profile	1.9 kg CO_2/kg	Steel deck	2.638 kg CO_2/m^3
Shear Connector – 105 mm	0.44 kg CO_2/unit	Concrete – 55 MPa	209.23 kg CO_2 m^3
Concrete – 20 MPa	141.10 kg CO_2/m^3	Concrete – 60 MPa	215.64 kg CO_2/m^3
Concrete – 25 MPa	150.62 kg CO_2 m^3	Concrete – 65 MPa	221.59 kg CO_2/m^3
Concrete – 30 MPa	161.07 kg CO_2/m^3	Concrete – 70 MPa	227.14 kg CO_2/m^3
Concrete – 35 MPa	172.10 kg CO_2/m^3	Concrete –75 MPa	232.34 kg CO_2/m^3
Concrete – 40 MPa	180.71 kg CO_2/m^3	Concrete – 80 MPa	237.23 kg CO_2/m^3
Concrete – 45 MPa	194.68 kg CO_2/m^3	Concrete – 85 MPa	241.85 kg CO_2/m^3
Concrete – 50 MPa	202.28 kg CO_2/m^3	Concrete – 90 MPa	246.22 kg CO_2/m^3

2.2. Constraints for the composite cellular beam

Aiming to meet the criteria of ultimate limit states (ULS) and serviceability limit state (SLS) prescribed Lawson and Hicks [25] adapted to the Brazilian standardization, the constraints are presented in Eq. 10 to 18, as done by Badke Neto [26] and Ramos and Alves [14].

$$1-\frac{M_{o,Rd}}{M_{Sd}}\leq 0 \tag{10}$$

$$1-\frac{V_{Rd}}{V_{Sd}}\leq 0 \tag{11}$$

$$1-\frac{M_{VRd}}{V_{Sd}l_e}\leq 0 \tag{12}$$

$$1-\frac{V_{wp,Rd}}{V_{wp,Sd}}\leq 0 \tag{13}$$

$$1-\frac{M_{wp,Rd}}{M_{wp,Sd}}\leq 0 \tag{14}$$

$$1-\frac{N_{wp,Rd}}{N_{wp,Sd}}\leq 0 \tag{15}$$

$$1-\frac{V_{Rd1}}{V_{Sd}}\leq 0 \tag{16}$$

$$1-\frac{V_{Rd2}}{V_{Sd}}\leq 0 \tag{17}$$

$$1-\frac{\delta_{lim}}{\delta}\leq 0 \tag{18}$$

$$1-\frac{\eta}{\eta_{min}}\leq 0 \tag{19}$$

Where, for $L\leq 25m$:

$$\eta_{min}=maximum\left[1-\frac{355}{f_y}\cdot(0.75-0.03L)\,;0.4\right] \tag{20}$$

3. Results and Discussions

3.1. Program Validation

In order to validate the developed program, a verification of the ultimate limit states is made with a problem mentioned in literature. The case in question is a meter cellular composite beam applied to a parking lot, initially proposed by Oliveira [27], following European standardization, and later also being verified by Badke Neto[26], according to the Brazilian standardization. A summary of the problem data is shown in table 2, and the results of the validation are presented in table 3.

Table 2. Problem Parameters

Geometric Parameters			
Beam Span (L)	10 m	Beam Spacing (b)	2 m
Alveoli Diameter (d_O)	400 mm	Diameter of Shear Connectors (d_c)	19 mm
Web-Post Length (s_O)	150 mm	Total Depth of Slab (h_s)	120 mm
Width of End-Post (s_e)	400 mm	Depth above Steel Decking (t_c)	60 mm
Material Properties			
Yield Strength of Steel (f_y)	235 MPa	Modulus of Elasticity of Steel (E_s)	210 GPa
Concrete Characteristic Strength (f_{ck})	30 MPa	Concrete Modulus of Elasticity (E_s)	33 GPa
Yield Strength of Connectors (f_y)	350 MPa	Connectors Ultimate Tensile Strength	450 MPa
Chosen Profile	IPE 550	Linear Mass	105 kg/m
Loading Data			
Dead Load Factor (γ_g)	1,35	Live Load Factor (γ_q)	1,5
Utilization Phase		Construction Phase	
Total Dead Load (g)	10.1 kN/m	Total Dead Load (g)	1.35 kN/m
Total Live Load (q)	15 kN/m	Total Live Load (q)	kN/m

Table 3. Validation of the Problem.

	Opening Collapses			Web-Post Collapses			Shear Restrictions		Service
	$\frac{M_{Rd}}{M_{Sd}}$	$\frac{V_{Rd}}{V_{Sd}}$	$\frac{M_{VRd}}{V_{Sd} l_e}$	$\frac{V_{Rd}}{V_{Sd}}$	$\frac{M_{Rd}}{M_{Sd}}$	$\frac{N_{Rd}}{N_{Sd}}$	$\frac{V_{Rd}}{V_{Sd}}$	$\frac{V_{Rd}}{V_{Sd}}$	$\frac{\delta_{lim}}{\delta}$
Badke Neto [26]	72.3%	57.5%	53.0%	61.8%	0%	46.3%	45.0%	49.4%	63.7%
Authors	72.3%	58.4%	53.8%	61.8%	0%	46.5%	45.4%	49.7%	63.7%
Difference	0.0%	0.9%	0.8%	0%	0%	0.2%	0.0%	0.0%	0%

The results show a difference inferior to 1% in relation to the results of Badke Neto [25], probably due to approximation methods of the data sources, but, in general, confirming the accuracy of the program.

3.2. Optimization

After the validation of the program efficiency, it is made an optimization of the same problem, first with total interaction and with partial interaction. For that matter, it is considered an expansion factor of 1.35 and length between openings of $1.5d_O$. Because no data concerning the steel deck load capacity was found, it was chosen to maintain the slab properties constant, that is, x_2 restricted to the initial value of 30 MPa. Table 6 presents a comparison between the solutions. In order to meet the minimum yield strength of the steel profile prescribed by ABNT NBR 8800:2008 [18] as 250MPa, table 6 also shows the results when a Brazilian commercial steel, with yield strength of 345MPa, is used with commercial equivalent formwork. Figure 2 presents a relation of the security criteria verification of each solution, as stated in Eq. 10 to 18, comparing the results of the initial solution and the optimization with full and partial interaction.

Table 6. Analysis of solutions.

Parameter	Initial Solution	Total Interaction	Partial Interaction	Brazilian Standarts
Chosen Profile (x_1)	IPE 550	W 530x85	W 530x85	W 530x66
Characteristic Strength (x_2)	30 MPa	30 MPa	30 MPa	30 MPa
Degree of Interaction (x_3)	100%	100%	67%	74%
Number of Connectors (n_{sc})	100	38	26	36
Steel Yield Strength (f_y)	235 MPa	235 MPa	235 MPa	345 MPa
CO_2 Emission ($CO_{2,total}$)	2959.99 kg	2530.6 kg	2525.2 kg	2251.6 kg
Relative Economy	-	14.5%	14.7%	23.9%

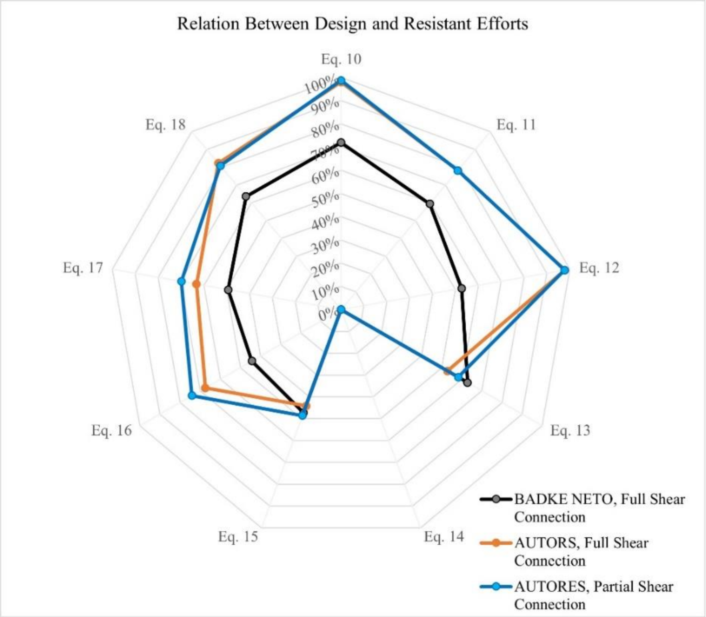

Figure 2. Relation between Design and Resistant Efforts.

As shown in table 6, the structural optimization is able to avoid a significant amount of CO_2 emission, reaching more than a 14% reduction. The use of partial interaction also shows a reduction of the use of 12 shear connectors while still obeying the security criteria, being a more economical solution. Figure 2 confirms this statement by showing that the consideration of partial interaction makes a better exploitation of the resisting capacity of the composite structure. Furthermore, table 6 also reveals that the use of a different steel demonstrates a significant reduction of steel mass, resulting on a profile with 66 kg/m, 37.1% lighter than the initial solution, in accordance with the results found by Ramos and Alves [14].

4. Conclusions

This work presented a program capable to verify the structural security of composite cellular beams and optimize it, finding the combination of steel profile geometry, concrete's characteristic strength and degree of interaction that has the smallest CO2 emission and meets the security criteria. The structural analysis is validated with a literature problem and showed less than 1% difference in relation to the reference, demonstrating its efficiency. When applying the optimization formulation, a reduction in the structural mass of the profile was found and consequently a reduction in CO2 emission in the profile's production process. For the studied example, although the f_{ck} parameter was a design variable, the solution converged to the smallest value. However, when changing the type of structural steel, a 37.1% reduction was found. In conclusion, it can be affirmed that the use of an optimization program is capable to significantly reduce the CO_2 emission and the consideration of partial interaction improves the results even more.

Acknowledgements. The authors thank FAPES and CAPES for the financially supporting this research.

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