Environmental Impact and Cost Analysis on the Optimum Design of Composite Frame System

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Abstract: The objective of the present work is present the optimization problem with a focus on the financial and environmental impacts of a system formed by a column of steel columns that support a floor with beams and composite slabs of steel and concrete, steel deck formwork welded on beams, reinforcing steel mesh, crack reinforcement and different concrete compression strength (f_{ck}). The genetic algorithm was used to find the solution to the optimization problem and the objective function is composed of CO_2 emissions from the above-mentioned components. An example has been studied to demonstrate the effectiveness of the proposed formulation. In this example, the concrete f_{ck} was varied to a value of 50MPa for the analysis and comparison of emission values. The results indicated a reduction in CO_2 emissions and financial cost.

Keywords: Composite Frame, Genetic Algorithm, Optimization, Environmental Impact

1 Introduction

Since the industrial revolution in the 18th century, the amount of air pollution has increased significantly. In recent years this situation has worsened and forced countries to commit to reducing pollution. In this context, the civil construction is inserted, which has in its practice a notorious emission of polluting gases throughout the construction cycle of the works. Thus, it is extremely necessary to reduce the CO_2 emissions of the structures.

It isn't new to use composite systems to reduce the environmental impact caused by composite structures, as these have some benefits compared to reinforced concrete. Erdal *et al.*[1] point out that among the benefits, span size and foundation costs are the main advantages in using a composite system. In addition, Zula *et al.* [2] performed the optimization of a system composed of floor and composite beam. The optimization method was through the Composite Integer Nonlinear Programming (MINLP) algorithm. In that same line Jia *et al.* [3] he conducted an experimental study of the behavior of composite beams of tubular slabs submitted to bending and eventual optimization of the main constructive parameters.

In optimization problems, gradient-based methods converge rapidly to a solution, but as Kaveh [4] points out, this method is not efficient because of the high. nonlinearity of structural problems and the high level of error (convergence to local minimums). Thus, the use of meta-heuristic algorithms for the modeling of optimization problems is very satisfactory. Based on this the optimization of steel structures was formulated by Degertekin [5] through the Harmonic Search (HS) algorithm proposed by Geem and Kim[6] which is based on the improvisation process of jazz musicians, where perfect harmony between all components of the objective equation is sought. Bakhshpoori and Kaveh [7] proposed an algorithm for structural optimization problems, called Water Evaporation Optimization (WEO) that is inspired by the evaporation of a tiny group of water molecules. De Lazzari, Alves and Calenzani [8] performed structural optimizations of steel frames and Breda, Pietralonga and Alves [9] made a study of composite floor optimization considering only the secondary beams via Genetic Algorithm.

Talking about the optimization of sustainability parameters in structures, Paya-Zaforteza *et al.* [10] they carried out a work where the cost and CO_2 emissions of 6 flat concrete gantries reinforced with the Simulated Annealing algorithm are optimized, which analogizes a metallurgy cooling process.

Kripka and Medeiros [11] emphasize environmental damage caused by the transportation and manufacture of reinforced concrete inputs. Thus, a study was carried out to optimize the monetary and environmental costs of reinforced concrete columns, rectangular, subjected to compression and bending loads through HS. Environmental emissions were determined by analyzing the concrete life cycle. In the work of Tormen *et al.* [12] the formulation for optimization is carried out with the use of Harmonic Search of CO_2 emission in composite beams of steel and concrete bisupported and subjected to bending.

In view of the above, the objective of this work is to present the formulation and application of the optimization problem for a spatial frame system composed of I columns profiles and composite floor system composed of beams and steel deck formwork. An analysis of the optimal solution from both the point of view of CO_2 emission and cost will be carried out. An example of the literature will be compared with the proposed formulation, in order to validate the problem. To solve the problem will be used the Native Genetic Algorithm of Matlab[13].

2 Methodology

2.1 General analysis characteristics

For the implementation of the optimization problem, the Composite Frame application will be developed within the Matlab platform. The program is based on the routines described in ABNT NBR 8800:2008[14] of a composite steel and concrete floor system, with steel deck for the slab and steel columns taking as objective function the minimization of CO_2 emissions. The steel deck form are defined based on the Metform catalogue [15], the steel profiles for the beams and columns that can be type I, H, CS, VS and CVS and are present in the Gerdau company catalogue [16].

The objective function that was proposed in this work is due to the emission from each component of the analyzed composite floor system. The Equation 1 shows the composition of this objective function with the sum of each part.

$$Minimize\ CO_2 = CO_{2(beam)} + CO_{2(formwork)} + CO_{2(concrete)} + CO_{2(mesh)} + CO_{2(column)} \tag{1}$$

Where:

$CO_{2(beam)}$ is the emission of the beams;

$CO_{2(formwork)}$ is the emission of the steel deck form;

$CO_{2(concrete)}$ is the emission of concrete;

$CO_{2(mesh)}$ is the emission of the steel mesh;

$CO_{2(column)}$ is the emission of the columns;

Table 1 presents the reference values of CO_2 emissions used in this study. The amount of CO_2 in kg per m^3 of concrete, according to resistance class is similar to the values used by Santoro and Kripka [17]. The CO_2 emission in kg per kg of the steel used for manufacturing profiles, reinforcement bars and shear connectors were extracted from the life-cycle evaluation (LCE) database for the steel industry provided by Worldsteel Association [18].

Table 1. CO_2 emission of materials

Material	Unit	CO_2 emissions ($kgCO_2$)	Reference
Concrete 20 MPa	m^3	130.68	Santoro and Kripka [17]
Concrete 25 MPa	m^3	139.88	
Concrete 30 MPa	m^3	148.28	
Concrete 35 MPa	m^3	162.36	
Concrete 40 MPa	m^3	172.77	
Concrete 45 MPa	m^3	185.32	
Concrete 50 MPa	m^3	216.40	

Steel deck	kg	2.6380	Worldsteel Association [18]
Steel profile	kg	1.1160	
Stud bolt shear connector	kg	1.1160	
Reinforcing steel mesh	kg	1.9240	
Steel CA-50, ø 8 mm, rebar	kg	1.9240	

Another important factor to be considered in the analysis, design and optimization of structures are the constraints that should be imposed on the problem in order to converge to the absolute minimum. Constraints model the sample space that the optimization algorithm will search for solutions, that is, this function is the one that restricts the solutions that the algorithm will follow to solve the proposed problem. These constraints are based on Annex O of NBR 8800:2008 and on design parameters. The 16 constraints imposed on the algorithm are presented in equation 2.

$$C=\begin{cases} \dfrac{h_w/t_w}{5{,}7\sqrt{E/f_{yk}}}-1\leq 0 & \dfrac{h_{wp}/t_{wp}}{5{,}7\sqrt{E/f_{yk}}}-1\leq 0 \\ \dfrac{\alpha_{min}}{\alpha}-1\leq 0 & \dfrac{\alpha_{min,p}}{\alpha_p}-1\leq 0 \\ \dfrac{M_{sd}}{M_{rd}}-1\leq 0 & \dfrac{M_{sd,p}}{M_{rd,p}}-1\leq 0 \\ \dfrac{V_{sd}}{V_{rd}}-1\leq 0 & \dfrac{V_{sd,p}}{V_{rd,p}}-1\leq 0 \\ \dfrac{\delta_t}{\delta_{adm}}-1\leq 0 & \dfrac{\delta_{t,p}}{\delta_{adm,p}}-1\leq 0 \\ \dfrac{M_{Sd,0}}{M_{Rd,0}}-1\ \leq 0 & \dfrac{M_{Sd,0,p}}{M_{Rd,0,p}}-1\ \leq 0 \\ \dfrac{H_{v,Sd}}{H_{v,Rd}}-1\ \leq 0 & \dfrac{H_{v,Sd,p}}{H_{v,Rd,p}}-1\ \leq 0 \\ \dfrac{N_{Sd}}{N_{Rd}}-1\ \leq 0 & \dfrac{q_{sd}}{q_{rd}}-1\leq 0 \end{cases} \tag{2}$$

Where:

h_w	is the height of the steel profile table;
t_w	is the thickness of the steel profile table;
α_{min}	is the minimum degree of interaction allowed to the composite beam;
α	is the degree of interaction of the composite beam;
M_{sd}	is the requesting bending moment;
M_{Rd}	is the tough bending moment;
V_{sd}	is the shear effort requesting;
V_{rd}	is the tough shear effort;
δ_t	is the total deflection of the beam;
δ_{adm}	is the permissible deflection of the beam;
$M_{Sd,0}$	is the requesting bending moment before the cure of concrete;
$M_{Rd,0}$	is the tough bending moment before the cure of concrete;
$H_{v,Sd}$	is the corresponding design to shear force requesting;
$H_{v,Rd}$	is the corresponding design to shear force resistant;
N_{Sd}	is the normal effort requesting;
N_{Rd}	is the normal effort resistant;
q_{sd}	is the uniformly distributed live load on the slab;
q_{rd}	is the live-load capacity of the slab;

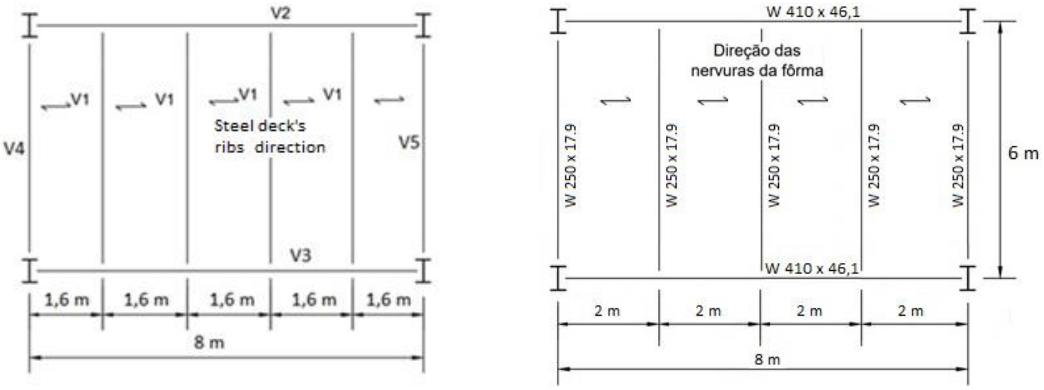
It is interesting to see the symmetry between the constraints, in which the variables without subindexes represent the constructive parameters of the secondary beams and the variables with subindexes p represent the main beams.

2.2 Optimization Method

The algorithm used for the optimization of structures is the Genetic Algorithm (GA) proposed by Holland [19] and which presents the necessary conditions for the optimization of problems with high nonlinearity rates. It is based on the evolutionary theory of Charles Darwin, who among other conclusions showed that adaptability is what differs the survival and extinction of a species. Bringing to the computational world the GA makes changes, through mechanisms of mutation, selection, recombination and crossing, in any initial population, to adapt to the constraints that are imposed for its existence.

3 Example

To show the efficiency of the proposed problem, the formulation is compared with the work of Poitras, Cormier and Nabolle [20], in which composite steel deck slabs were analyzed. For optimization, a new heuristic algorithm entitled Peloton Dynamics Optimization (PDO) was proposed, based on the behavior of platoons of cyclists during races. The sample space of the steel deck form consists of two different thicknesses (0.76 and 0.91 mm). At this first time the columns will not be included in the optimization because the example originally didn't do this optimization. Thus, the result of the example for the dimensions of a slab of 6m long by 8m wide presented 4 V1 interior beams with profile W 310 x 24, main beam V2 and V3 with W 530 x 74 and W 460 x 52 respectively and beams of V4 and V5 edges parallel to the V1 with profiles W 310 x 24 and W 310 x 21. The concrete of the slab adopted in the evaluations was 20 MPa. After modeling in the proposed algorithm, some modifications were verified. The show the arrangement proposed by Poitras, Cormier and Nabolle [17] and the arrangement and number of beams result from the optimal solution of the genetic algorithm. Interestingly, the solution proposed by the authors presents different beams for V2 and V3.



(a) *Poitras, Cormier and Nabolle [20]* (b) *Authors*

Figure 1. Optimal Solutions Found

With the provisions of the secondary beams presented in Figure 1, we were able to calculate the total emission of each component of the structures and determine whether there was an improvement in emission with the use of the genetic algorithm. The Table 2 shows the comparisons of emissions (in kgCO$_2$) of the solutions proposed by the authors.

Table 2. Emission of structure elements.

Elements	Poitras, Cormier e Nabolle [20]	Authors
Secondary Beams	944.14	597.02
Main Beams	1124.93	952.07
Steel deck formwork	1076.30	1186.46
Slab concrete (20 MPa)	564.54	878.97
Reinforcing steel mesh	111.75	111.75
Total	3824.65	3726.27

As can be seen, the optimized solution reached an optimal solution with a greater thickness of the concrete cover and with the largest steel deck (MF-75) shape, the modifications caused a small reduction in CO_2 emission (2.5%). The elements that didn't present a significant reduction in relation to the solution of Poitras, Cormier and Nabolle [20] were the concrete cover and the steel deck formwork. A probable reason for the increase in thickness of these elements is the reduced strength of the concrete.

To analyze the impact on concrete on the final result of optimization, new examples were analyzed with the f_{ck} ranging from 5 MPa to 50 MPa, in order to verify if there will be an improvement in the optimization results. For this verification, the optimal dimensioning of the columns was performed considering a length of 3m for the complete analysis of the system. For this analysis it was considered that the beams will transfer only normal load to the columns. Table 2 presents these results.

Table 3. Constructive characteristics of the example

Information	Un.	20 MPa	25 MPa	30 MPa	35 MPa	40 MPa	45 MPa	50 MPa
Number of secondary beams	un	5	5	5	4	4	6	5
Steel deck thickness	--	MF-75	MF-75	MF-75	MF-50	MF-75	MF-75	MF-75
Formwork's shape	mm	0.8	0.8	0.8	0.8	0.95	0.8	0.8
Maximum span	m	2.2	2.4	2.3	2.7	3.15	2	2.3
Total height of the slab	cm	14	14	15	15	14	15	14
Thickness of the concrete layer	cm	6.5	6.5	7.5	10	6.5	7.5	6.5
Reinforcing steel mesh	--	Q-75 (ø3.8-150x150)	Q-75 (ø3.8-150x150)	Q-75 (ø3.8-150x150)	Q-113 (ø3.8 -100x100)	Q-75 (ø3.8-150x150)	Q-75 (ø3.8-150x150)	Q-75 (ø3.8-150x150)
Profile of the secondary beam	--	W 250 x 17,9	W 250 x 17.9	W 200 x 15	W 200 x 17.9	W 310 x 21	W 250 x 17.9	W 250 x 17.9
Degree of composite interaction secondary beams	--	0.71	0.59	0.65	0.75	0.53	0.51	0.5
Total number of connectors secondary beams	un	90	80	70	80	64	84	70
Profile of the main beam	--	W 410 x 46.1	W 460 x 52	W 410 x 46.1	W 460 x 52	W 530 x 66	W 360 x 39	W 410 x 46.1
Degree of composite interaction main beam	--	0.56	0.56	0.71	0.53	0.76	0.88	0.71
Total number of connectors main beam	un	48	48	56	48	84	60	56
Column Profile	un	W 360 x 64	W 530 x 72	W 360 x 44.6	W 530 x 72	W 530 x 66	W 310 x 52	W 360 x 44.6
TOTAL CO_2 emission	kg	4585.86	4226.71	4372.09	5506.55	5730.05	4830.07	4695.26
TOTAL Financial Cost	R$	25897.47	27502.3	22943.29	27417.25	29360.75	25051.83	24272.07

Through the analysis of Table 3 it is possible to see the reduction of CO_2 emissions even with the increase in concrete resistance in some cases. From a cost point of view, the best solution for the 30MPa f_{ck}, while from the point of view of CO_2 emission the best solution was for the f_{ck} of 25 MPa. The most significant differences are shown in the number of secondary beams presenting a difference of up to 2 beams between the extremes of the solutions. This difference can be evidenced in the linear mass of these beams, and where there are more beams the linear masses of the profiles tend to have no smaller than the solutions with fewer beams. Figure 2 shows the discrimination of each structural element and how much each represents in the total emission of the structure.

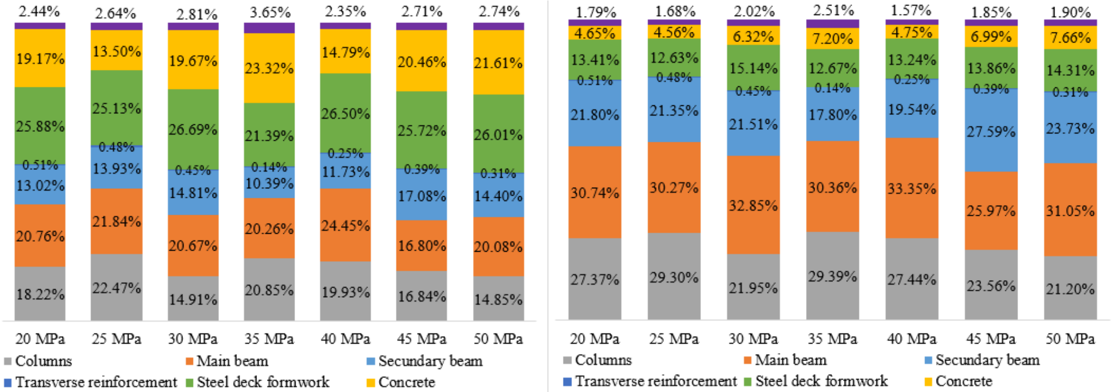


Figure 2. Emission e and cost of each component of the structure

It is worth noting that for all f_{ck} the steel deck form represented the highest CO_2 emission among all the materials of the structure. It is also possible to conclude that steel profiles, i.e., columns and beams represent, on average, more than 50% of all emissions from the solutions. If we take into account the steel deck, we reach a value of more than 75% of emission from steel materials (beams, columns and steel deck). The f_{ck} of 25 MPa presents the lowest of emissions, this behavior can be understood because of the reduction of the thickness of the slab that was presented in Table 3.

In addition to considerations for CO_2 emissions, Figure 2 shows the cost behavior of the solution structural elements for each f_{ck}. It is possible to notice a large portion referring to the total steel used, always representing a fraction greater than 90% of the entire cost of the structure.

Among the various constraints imposed on the problem, the main and most important for the analysis are those that refer to the ultimate limit states (ULS) of the beams and columns. The beams are sized at the moment of the deflector and cutting effort and the columns to the normal compression effort. The Figure 3 shows the utilization index of these constraints in the problem of optimization for the ULS of structural elements of different f_{ck}.

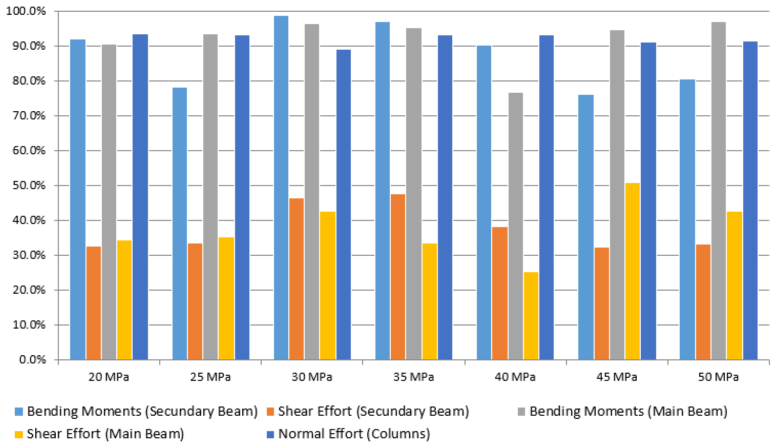


Figure 3. Optimization Percentage

The analysis of the constraints shows that the bending moments of the beams represent the most critical limit states, with averages of 92.2% and 87.7 for the main and secondary beams, respectively. The shear effort did not have a great impact. Therefore, it can be concluded that bending is a limiting factor of beam solutions. The columns presented a great optimization, being almost all above 90%. The f_{ck} of 20 MPa presented the highest optimization, reaching 93.7%.

4 Conclusion

After analyzing the results, it can be concluded that the emission performed for the concrete of 20 MPa presented a greater thickness of the concrete cover the reason for this choice can be noticed in the reduction of the number of secondary beams and also the profiles referring to the main and secondary beams when compared to the proposed problem.

Moreover, through the analysis with different f_{ck} values, there was a reduction in emission in the highest f_{ck}. The optimal value for emission occurred in the f_{ck} of 25 MPa and the financial cost occurred in the f_{ck} of 30MPa. By the financial contribution and emission of each analyzed element, it is perceived that the steel used is the material that emits the most CO_2, reaching 75% and 90% of emission and financial cost, respectively.

Finally, it is seen that the ultimate limit states that govern the stability of the beams is the bending moment reaching average values above 92% in the main beams. The results show the feasibility and potential of environmental impact reduction in relation to the formulation of the optimization of a system of steel columns, slabs and composite beams.

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