Analysis of CO_2 Emissions in the Topological Optimization of Floor Systems Composed by Composite Trusses

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Abstract. The use of composite floor systems in steel buildings has been growing over the last few decades. However, this application usually takes place with full web composite beams and composite slabs with incorporated steel formwork, although there are other possibilities, such as, for example, trusses composite beams. The objective of this work is to present the formulation of the topological and sizing optimization problem for floor systems composed of composite trusses with tubular steel profiles and composite slabs. A structure for the floor, secondary trusses are proposed that directly support the slabs and main trusses that serve as support for the secondary trusses. The trusses are simply supported and the upper compressed chord may or may not be filled with concrete. The objective function minimizes CO_2 emissions from the manufacture of materials used in the floor. The optimization problem solution was obtained via Genetic Algorithm (GA) and the Particle Swarm Optimization (PSO). The algorithm selects, in addition to the topology of the truss (height and number of truss panels), the ideal number of secondary trusses, the compressive strength of the concrete slab and the filling of the upper chord, and finally, it selects the profiles of the chords, diagonals and verticals and composite slab formwork from manufacturers' catalogues. The results indicate that, when compared with composite floor systems composed of full web beams, a reduction in CO_2 emissions of over 20% can be obtained depending on the spans of the analyzed floors. In addition, tubular trusses with a concrete-filled upper chord provide better solutions than trusses with an unfilled tube.

Keywords: Composite floor, Composite Tubular Trusses, CO_2 Emission, Genetic Algorithm, Particle Swarm Optimization

1 Introduction

Provide the appropriate arrangement of the various component elements of a structure is one of the essential design steps, as it provides the greatest resistant structure, efficiency, service performance and economy.

The implementation of composite floor systems has proven to be an efficient structural set, which consists of combining steel deck and concrete slab elements, forming an integrated system with the advantages of both materials. Although widely used with composite full web beams, the use of composite floor systems with composite trusses has been little used and is becoming increasingly widespread in the construction industry due to its structural and economic advantages. However, it should be noted that despite its growing popularity, the optimization of these systems is still a developing field of study.

Researchers study methods of optimizing steel structures through efficient automated processes with the purpose of minimizing the dependence on methods based on common practice. Azad [1] implemented the Monitored Convergence Curve (MCC) for the design of steel structures minimizing their weight. Bigham et al. [2] proposed improvement in electro-search algorithms to solve topological optimization problems of nonlinear single-layer domes. Mokarram et al. [3] demonstrated the optimization of spatial trusses structures with the expanded FC-MOPSO algorithm. Martínez Muñoz et al. [4] addressed the optimization of composite steel and concrete bridges considering their costs and CO_2 emissions through the metaheuristics SAMO2, SCA and Jaya.

The heuristic algorithms such as the Genetic Algorithm (GA) proposed by Holland [5] and the Particle Swarm Optimization (PSO) proposed by Kennedy and Eberhart [6] have proven to be good methods when dealing with numerous variables, such as topologies optimizations to find more efficient structural configurations. Studies with GA application can be found in the papers of Cruz et al. [7], Prendes-Gero et al. [8], Kim et al. [9], among others and with the PSO, we can mention Sun et al. [10], Harsono et al. [11] among others.

It should also be noted that the search for more sustainable solutions in the civil construction industry has become increasingly relevant due to the challenges faced in relation to climate change. In this context, the study of minimization of CO_2 emissions in structural systems has stood out as a promising approach to mitigate construction impacts, as can be seen in Santoro and Kripka [12], Alievi et al. [13], Arpini et al.[14], Erlacher et al. [15] among others. Given this scenario, the optimization of composite floor systems with composite trusses using optimization algorithms becomes essential to achieve an optimal structure in terms of design with the lowest environmental impact, since these studies are not yet widespread.

Therefore, the main objective of this paper is to propose the formulation of the topological and sizing optimization problem for a composite floor system with composite steel and concrete tubular trusses beams. The optimization problem solutions will be obtained via GA and PSO, and the tubular trusses beams will be evaluated with circular concrete-filled tubes (CCFT) and circular hollow tubes (CHT) in the upper chord.

2 Optimization Formulation Problem

2.1 Objective Function

The objective function to minimize the CO_2 emission of the composite floor system components is described in Equation 1, given in $kgCO_2$:

$$Min\ CO_2 = CO_{2(formwork)} + CO_{2(conc.slab)} + CO_{2(conc.filled)} + CO_{2(mesh)} + CO_{2(conectors)} + CO_{2(trusses)} \quad (1)$$

Where: $CO_{2(formwork)}$ represents the CO_2 emission generated by the steel deck formwork, $CO_{2(conc.slab)}$ is CO_2 emission generated by the concrete slab, $CO_{2(conc.filled)}$ is the total CO_2 emission generated by the concrete-filled the upper chords of the trusses for the adopted cases, otherwise its index is zero, $CO_{2(mesh)}$ refers to the CO_2 emission generated by the reinforcing steel mesh, $CO_{2(conectors)}$ corresponds to the CO_2 emission generated by all the shear connectors employed and $CO_{2(trusses)}$ is the total CO_2 emission generated by the profiles of the girder, edger and secondary trusses.

2.2 Design Variables

For the proposed problem, up to 17 decision variables were defined, as shown in Figure 1:

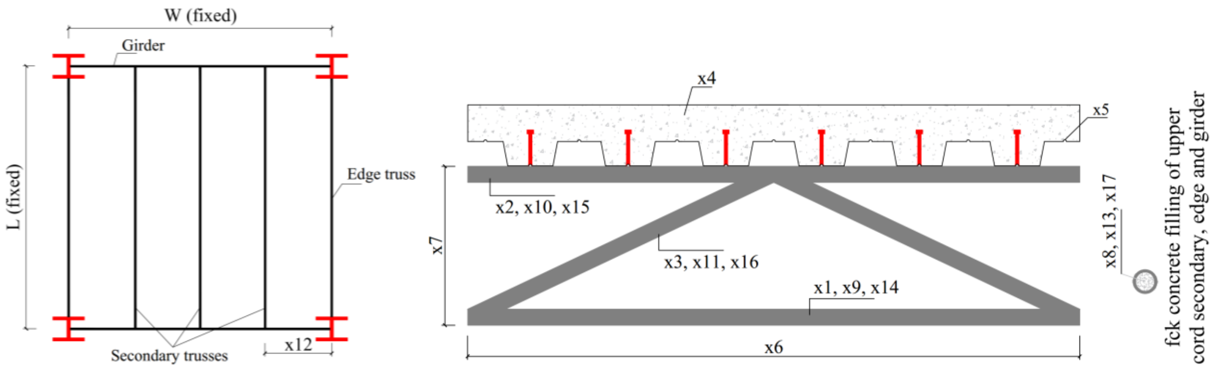

Figure 1- Decision variables of composite floor system with composite truss beams - (a) Indication of variable x_{12} (b) Indication of variables x_1 to x_{11} and x_{13} to x_{17}

Where: x_1, x_2, x_3: refer to the circular profile of the lower, upper chord and diagonal of the secondary trusses; x_4: f_{ck} of the floor slab; x_5: refers to the thickness of the steel deck formwork; x_6: refer to the number of truss panels; x_7: refer to the height of trusses; x_8: f_{ck} of the concrete-filled of the upper chord of secondary trusses; x_9, x_{10}, x_{11}: refers to the circular profile of the lower, upper chord and diagonals of the edges trusses; x_{12}: is the maximum span between trusses according to the Metform [16] catalog; x_{13}: f_{ck} of the concrete-filled of the upper chord of edge trusses; x_{14}, x_{15}, x_{16}: refers to the circular profile of the lower, upper chord and diagonals of the girder; x_{17}: f_{ck} of the concrete-filled of the upper chord of girder.

2.3 Constraints

The constraints follow the design criteria prescribed by ABNT NBR 16239: 2013 [17] for designing tubular profiles for Ultimate Limit State (ULS) and Serviceability Limit State (SLS). The analyzes are done separately for the upper and lower chord and web members profiles for each truss, before and after concrete curing, resulting in a total of 36 constraints that are represented below.

Analyzed Conditions	Equation	
Normal efforts	$C(1) = \frac{N_{Sd}}{N_{Rd}} - 1 \leq 0$	(2)
Composite Section Bending	$C(2) = \frac{M_{Sd,comp\ trusses}}{M_{Rd,comp\ trusses}} - 1 \leq 0$	(3)
Combined Bending of Upper Chord	$C(3) = \frac{N_{Sd}}{N_{Rd}} + \left(\frac{8}{9}\right) * \frac{M_{Sd}}{M_{Rd}} - 1 \leq 0$	(4)
Total deflection	$C(4) = \frac{\delta_{total}}{\delta_{máx}} - 1 \leq 0$	(5)

Constraint C(1) refers to the normal requesting forces of calculation for the upper, lower and diagonal flanges and uprights, before and after curing the concrete of the main and secondary trusses (internal and edge); C(2) refers to the limitation of design bending and resistant bending moment for the situations before and after curing of the composite section. Constraint C(3) concerns the combined verification referring to normal efforts and those due to bending and resistant moments, before and after concrete curing for the Upper flanges of secondary trusses (internal and edge) and constraint C(4) refers to the limitation of imposed displacements.

3 Results and Discussions

To demonstrate the application, the problem proposed by Arpini et al.[15] was analyzed. The authors analyzed CO_2 emissions in a floor system featuring steel-concrete composite girders and slabs. The problem solution was solved via GA and the analysis was applied to a floor of dimensions 7.5 m x 7.5 m with geometries and reference cross-section given in Figure 2. It was considering the concrete slabs with gneiss aggregate, ASTM GR 42 steel with f_y of 345MPa for trusses profiles, and steel deck formwork from the Metform catalog [17] produced with ASTM A653 galvanized steel and f_y of 280 MPa. The loading included the flooring and steel structure weight, a serviceability live load of 5 kN/m². Figure 2 presents the solution proposed by Arpini et al. [15].

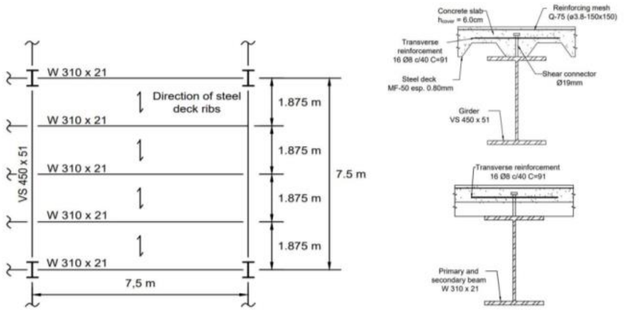

Figure 2 – Optimal geometry solution obtained by Arpini et al. [15] via GA

The problem was analyzed with circular profiles composite trusses and the solutions was obtained via GA and PSO. According to the results obtained by Erlacher et al. [15], Warren truss model provide better solutions when compared to other models of trusses. Therefore, Warren model were used for the edges and secondary trusses. For the girders, the Pratt truss model was adopted due to the need to have a vertical bar at the intersection of the trusses. For the upper chord profile, two possibilities are investigated, circular concrete-filled tubes (CCFT) and circular hollow tubes (CHT). Table 1 presents the profiles obtained for the trusses and Table 2 presents the comparative analysis between the solutions.

Table 1. Trusses profiles obtained to the optimal solutions and from Arpini et al. [14]

Data	Shape of profile	Alg.	Profile of the Edge Truss (mm)	Profile of the Secondary Truss (mm)	Profile of the Girder (mm)	Height (cm)	Nº Panels
Arpini et al. (2022)	Full web Profile	GA	W310x21	W310x21	W450x51	--	--
Authors (2023)	CHT	GA	BI:TC48.3x3.6 BS:TC60.3x3.6 DM:TC33.4x3.6	BI:TC88.9x4.0 BS: TC88.9x4.0 DM:TC38.1x3.2	BI:TC42.2.3x4.0 BS:TC88.9x3.6 DM:TC33.4x3.6	85	7
		PSO	BI:TC38.1x4.0 BS:TC73.0x3.6 DM:TC33.4x3.2	BI: TC88.9x3.6 BS: TC88.9x5.0 DM:TC38.1x3.6	BI:TC60.3x3.6 BS:TC88.9x5.0 DM:TC33.4x3.6	60	7
	CCFT	GA	BI:TC73.0x4.0 BS:TC42.2x4.5 DM:TC48.3x3.6 fck: 45 MPa	BI:TC60.3x3.6 BS: TC60.3x3.6 DM:TC48.3x4.0 fck: 45 MPa	BI:TC42.2x4.0 BS:TC60.3x3.6 DM:TC33.4x3.6 fck: 50 MPa	85	4
		PSO	BI:TC33.4x3.2 BS:TC33.4x3.2 DM:TC33.4x3.2 fck: 25 MPa	BI:TC42.2x5.0 BS:TC48.3x3.6 DM:TC42.2x4.5 fck:35MPa	BI:TC38.1x4.0 BS:TC60.3x3.6 DM:TC33.4x3.6 fck: 40 MPa	90	2

Table 2. Comparative analyses of the solutions

Information	Unit	Arpini et al. (2022)	Authors CHT		Authors CCFT	
		GA	GA	PSO	GA	PSO
Total height of the slab	cm	11	11	11	11	11
Thickness of the concrete layer	cm	6	6	6	6	6
fck of the slab	MPa	25	25	25	25	25
Steel deck formwork	--	MF-50	MF-50	MF-50	MF-50	MF-50
Steel deck thickness	mm	0.8	0.95	0.95	0.95	0.95
Maximum span steel deck	m	2.2	2.50	2.50	2.50	2.50
Reinforcing steel mesh	--	Q-75 (ø3.8-150 × 150)	Q-75 (ø3.8-150 × 150)	Q-75 (ø3.8-150 × 150)	Q-75 (ø3.8-150 × 150)	Q-75 (ø3.8-150 × 150)
Number of beams	un	5	4	4	4	4
Distance between beams	m	1.875	2.50	2.50	2.50	2.50
Total connectors of the edge trusses	un	48	16	16	16	16
Total connectors of the secondary trusses	un	32	16	16	16	16
Total connectors of the girders	un	28	8	8	8	8

According to Table 2, the number of secondary trusses were reduced with the increase of the span, on the other hand, the thickness of the formwork was increased due to load requirement. In addition, a difference in the height trusses can be noted when GA and PSO were used for solutions with hollow and concrete-filled tubes in the upper flange. For the slab was obtained the same characteristics for all proposed solutions. Figure 3 presents the final topology of the floor obtained via GA and PSO for the hollow and concrete-filled tubes in the upper flange and Figure 4 presents the ratio between the analyzed solutions to the total CO_2 emission and Figure 5 presents the CO_2 emission composition.

(a) CHT GA

(b) CHT PSO

(c) CCFT GA

(d) CCFT PSO

Figure 3 – Floor Final Geometries

As can be seen in Figure 4, all solutions are better when compared to Arpini et al. [14]. And the best results were PSO and GA with concrete-filled tubes. PSO provided the best solution with a reduction of approximately 24%. Figure 5 provides the ratio between the CO_2 emissions of the optimized solutions and the CO_2 emission of the solution by Arpini et al. [14], analyzing separately each element that makes up the composite floor.

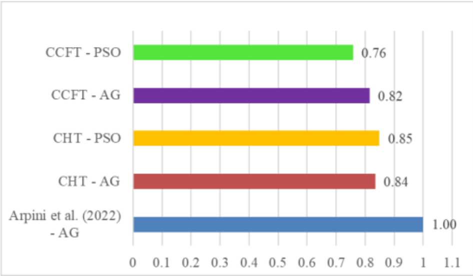

Figure 4 – Normalized solutions of total CO_2 emissions.

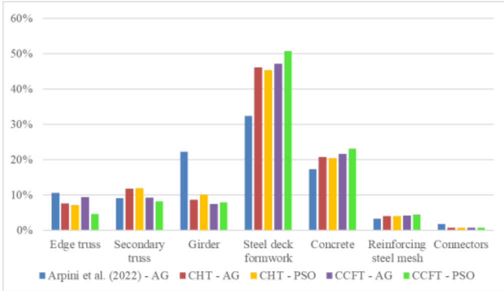

Figure 5 – CO_2 emission composition

As seen in Figure 5, except for the steel deck formwork, which presented a higher CO_2 emission, in the order of 20%, than the proposal by Arpini et al. [15], the other structural elements showed lower CO_2 emissions, and for the main beam, the reduction was around 60% for the best solution. It is also possible to verify a significant reduction in the shear connectors emissions, however, it is emphasized that these have a low weight in relation to the total emission of the composite floor system. Figure 7 presents the main constraints analysis of the problem.

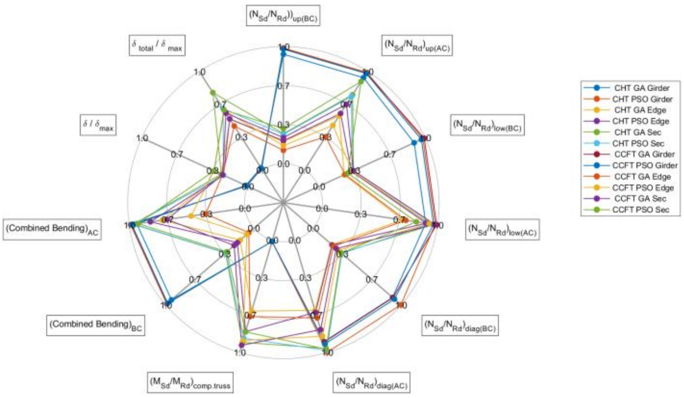

Figure 7 – Constraints Analysis

As seen in Figure 7, the normal stresses and the combined bending in the main trusses, for GA and PSO, with and without concrete filling, presents critical results before and after curing, with a rate of use of the main trusses (GA and PSO) virtually unchanged for the situations before and after curing, since they are dimensioned from point loads arising from the secondary trusses and unloaded at the truss nodes. This fact is also confirmed from the small influence of the bending moment in the design of these parts. On the other hand, the edge and internal trusses present significant normal stresses exclusively after curing, being more expressive in the lower chords, diagonals and uprights. For the internal trusses, the results of GA and PSO were different, with PSO provided critical values for diagonals and upper flange after curing and GA provides critical values in the parameters referring to the forces acting on the lower flange after curing and bending moments.

4 Conclusions

In analysis of the results with the proposed formulation, it can be concluded that both GA and PSO were efficient in obtaining the solution of the optimization problem, with PSO achieving the best results. The best solution obtained was with circular concrete-filled tubes for the 3 trusses, with a reduction for the best solution of 24% of the final emissions. It is worth mentioning, even the highest strength concretes with a greater CO_2 emission, their use in CCFT significantly reduces the final emissions of the floor, and this reduction was around 8% when compared to the two solutions obtained via PSO. Regarding the governing criteria of the problem, it was observed that the combined bending of the upper chord, the tensile stresses on the lower chord and the bending of the composite section had a strong influence on the final solution.

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