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Optimization of steel-concrete composite beams considering cost and environmental impact

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Abstract. In the optimized structure sizing, the optimization methods are inserted in this context in order to obtain satisfactory solutions, which can provide more economical structures, besides allowing the consideration of the factors related to the environmental impacts in the structural design. This work proposes a mathematical model for the optimization of steel-concrete composite beams aiming to minimize the monetary cost and the environmental impact, using the Harmonic Search optimization method. Discrete variables were the dimensions of the steel profiles and the thickness of the collaborating slab of the composite steel-concrete beam. The proposed model was implemented in Fortran programming language and based on improvements in the structure of the optimization method proposed by Medeiros and Kripka (2017). To prove the effectiveness and applicability of the model, as well as the Harmonic Search method, analyzes were performed with different configurations of steel-concrete composite beams, in order to provide guidelines that make the use of these systems more streamlined. In general, the Harmonic Search optimization method has proved to be efficient in the search for the optimized solutions, as well as important considerations on the optimization of the monetary and environmental costs of steel-concrete composite beams were obtained from the developed examples.

Keywords: optimization; steel–concrete composite beams; Harmonic Search; composite beams

1. Introduction

The traditional process of structural design is based on analyzing several solutions, the feasibility of their execution and then selecting the best design option. The chosen option will be the one that has a projected system that satisfactorily performs the service functions, is efficient, safe, and functional, and, most importantly, provides a good cost–benefit relationship and promotes the sustainability of the projected structures.

Besides the technical and economic approaches, environmental issues have been strongly emphasized defended in recent years to assess the impacts generated in obtaining and executing the necessary elements for the construction of a specific civil work. In an indirect way, structural optimization is closely linked to environmental sustainability, which can be promoted by the lower consumption of materials and the rationalization of available natural resources (Payá-Zaforteza *et al*. 2009, Yepes *et al.* 2012, Camp and Huq 2013, Camp and Assadollahi 2013, Park *et al*. 2013, Medeiros and Kripka 2014, Yeo and Potra 2015, Yepes *et al.* 2015, Fabeane *et al.* 2017).

In addition to the economic and environmental bias, efforts have been made to improve the properties and characteristics of structural materials. Composite materials, also called mixed materials, have been widely used and are gradually replacing traditional materials for a wide range of purposes, especially in the aeronautical, automotive, railroad, and naval transport industries (Reddy 2004). These materials have advantages, such as high stiffness, high strength/weight ratio, corrosion resistance, fatigue resistance, improved fire protection, and greater flexibility to adjust their properties compared to conventional structural materials (Pelletier and Vel 2006).

One of the structural systems currently used in building construction is the steel–concrete mixed system. This combines the main characteristics of both materials, including the tensile strength of the steel with the compressive strength of the concrete, as well as other positive factors, which include: good stability due to the high concrete mass; a lower cost due to the accelerated process of industrialization, which is directly related to the standardized manufacturing of the elements; agility in assembly, especially for the steel forms, since there is no

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need for total cure of the concrete for continuity of the execution of the assembly (Fabeane *et al*. 2017).

Composite steel-concrete structures are employed extensively in modern high-rise buildings and bridges. For this reason, several studies have been developed in this field. For example, Mirza and Uy (2010) developed an accurate finite element model to study the behavior of shear connectors in push tests including the time-dependent behavior of concrete. An exact dynamic stiffness method was introduced by Li *et al*. (2014) to investigate the free vibration characteristics of steel-concrete composite beams with stud connectors. Lezgy-Nazargah and Kafi (2015) proposed a finite element model for the analysis of composite steel-concrete beams based on a refined high-order theory. Zhou *et al*. (2016), conducted a study to investigate the equivalent lateral and torsional restraint stiffnesses of the bottom flange of an I-steel concrete composite beam under negative moments. Luo, Zhang, and Li (2019) analyzed the shear lag effect in steel-concrete composite beam in hogging moment. Still, Davoodnabi, Mirhosseini, and Shariati (2019) studied free vibrations of steel-concrete composite beams by using the dynamic stiffness approach.

However, because mixed systems consist of different materials, their design has a greater number of design variables, which makes it difficult to determine a configuration that provides excellent performance based on the usual trial and error strategies. In this case, optimization techniques can provide a more refined adjustment for the definition of design demands for such variables and parameters of structural design (Reis *et al*. 2011).

The success of the structural design depends on the validity and adequacy of the models used in the design, an analysis of the behavior of the elements, as well as on the sensitivity of the parameters (Doltsinis and Kang 2004). Thus, the optimization techniques of structures combined with computational programming allow, in a systematic way, searching for the best possible solution to some problem through an iterative process, or at least a value very close to it, even in a wide space of solutions (Carbonell; Yepes; González-Vidosa 2011). Such techniques are based on an objective function by which the quality of the solution is evaluated and can be related to cost, weight, cross-sectional area, or any other desired parameter based on the design criteria and constraints in addition to regulatory requirements.

Molina-Moreno *et al*. (2017) point out that metaheuristic algorithms are solution methods that coordinate local search procedures with higher-level strategies to create a process capable of escaping from local minimums and performing a robust search in the solution space of a problem. Several heuristic search algorithms belong to this category, including the Harmonic Search method, which was developed analogously to the process of obtaining the best musical harmony (Geem *et al*. 2001).

In the field of steel-concrete composite beam optimization, several studies have proposed different techniques aiming the reduction of cost or weight of these structural elements (Kravanja and Silih 2003, Senouci and Al-ansari 2009, Alankar and Chaudhary 2012, Eskandari and Korouzhdeh 2016, Korouzhdeh *et al.* 2017), on floor systems (Adeli and Kim 2001, Klansek and Kravanja 2006a and 2006b, Rosça *et al.* 2012, Munck *et al.* 2015, Kravanja *et al.* 2017), on bridges (Toma and Maeda 2011, Gocál and Dursová 2012, Kaveh, Bakhshpoori and Barkhori 2014, Fabeane *et al.* 2017), on bonded bonding between the elements (Luoa *et al.* 2011) considering the effect of adhesion among different material interactions (Zheng *et al.* 2011) and replacement of shear connectors with adhesives (Yangjun and Li 2012).

Although several studies related to the optimization of steel-concrete composite beams can be found in technical literature, only the economic approach is addressed in order to reduce monetary costs. However, the need for studies that consider beyond the economic approach, the environmental approach, is notorious, since this issue has been widely discussed today.

Thus, this work aims to find solutions that minimize monetary costs and environmental impacts generated by the use of steel-concrete composite beams.

1.1 Optimization

In general, an optimization problem can be defined as a process of determining the minimum or maximum of some function, called the objective function, from which an optimal solution is sought. Project variables and parameters are constants that define the physical problem, so as to satisfy the constraints to which these variables are subject.

In structural engineering, optimization can be understood as a process that provides a better configuration of the structure, which is applied to a wide range of problems in an attempt to determine an optimum design in terms of performance and form; better layout and positioning of elements; better sets of material, topology, geometry and/or cross dimensions for different structural systems; and reduction of existing costs (weight, transport, assembly, construction time, costs related to ruin and structure efficiency) (Payá-Zaforteza *et al*. 2010, Suji *et al*. 2008). The different optimization methods are characterized by the strategy adopted in the search for an optimal solution.

The reasons for the limited applications of optimization techniques to real structural problems are related to the inherent complexity of the models generated (Lagaros *et al*. 2006), which tend to have several local minimums and are usually described by nonlinear and discontinuous functions, generating a space of solutions with multiple optimum points.

The methods of mathematical programming, also called classic methods, have some limitations, such as the difficulty of working with discrete variables and non-differentiable functions and identifying optimal global solutions, as such methods are dependent on the starting point or initial estimate. These methods operate in a deterministic way; that is, they always follow the same process to obtain the optimal solution and provide the same result for a given input parameter.

Due to the limitations of these methods, the implementation of non-deterministic optimization methods, known as metaheuristic methods, has grown considerably.

These are based on stochastic or probabilistic algorithms, which are based on the probability of events, the refinement of possible solution sets, and direct evaluation of the objective function, not depending on derivatives, which are also called zero-order methods.

Heuristic methods, whose development is linked to the evolution of artificial intelligence procedures, base their search process on analogies with natural, cultural, social, biological phenomena, or laws of physics that specify the processes of research (Voβ 2001). These methods have been successfully implemented in different areas of structural engineering (Yepes and Medina 2006, Geem and Sim 2010) and include a large number of algorithms, such as Simulated Annealing methods, genetic algorithms, ant and bee algorithms, Harmonic Search, and particle swarm optimization (Jones 2003, Kripka *et al*. 2015). In addition to these widely used optimization methods, it is important to stress the growing application of other recent algorithms for use in structures, such as Jaya optimization algorithm for optimum design of steel grillage structures (Dede 2018) and the Teaching-learning-based Optimization algorithm (TLBO) for fundamental frequency optimization of simply supported antisymmetric laminated composite plates (Topal *et al*. 2017).

Harmonic Search (HS) is an optimization heuristic inspired by the process of improvisation or musical performance whereby musicians seek to achieve a better state of harmony, or perfect harmony. In music, this perfect harmony is considered analogous to finding the optimum solution to an optimization problem and refers to a given audio quality standard.

Analogously to the process of musical improvisation, each musician plays a sound referring to his instrument, generating a vector of harmony in the optimization problem. The improvisational ability of the musicians to obtain new harmonies takes into account the frequency, timbre, and amplitude of each of their instruments. Based on this analogy, Geem (2010) utilized a jazz trio composed of a saxophonist, a bass player, and a guitarist to compose a decision variable of the problem based on each instrument. The notes played on the instruments represent the range of values of each variable, while the combinations of the notes represent the possible solutions. The listeners' appreciation represents the evaluation, or objective function of the problem, as shown in Fig. 1.

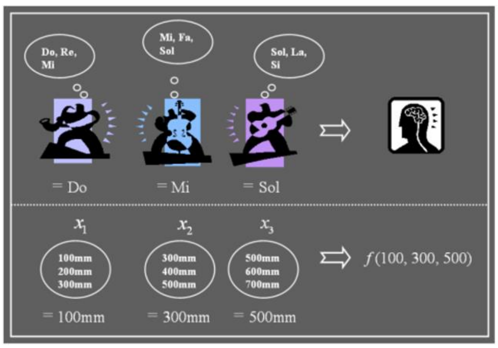


Fig. 1 Optimization and Improvisation (Geem 2010)

The HS algorithm includes a number of optimization operators (Geem *et al.* 2001), such as Harmony Memory (HM), Harmony Memory Size (HMS), Harmony Memory Consideration Rate (HMCR), Pitch Adjustment Rate (PAR), Maximum Number of Improvisations (NI), and the Bandwidth (BW). Initially, the algorithm proposes a set of solutions, which represent the initial suggestions of the musicians. To obtain the value of the objective function, which is called aesthetic estimation, we evaluate the set formed by the sounds (numerical value) of each instrument (variable). A new vector is generated by the random selection of components of different HM vectors, which are stored in the HM. If all sounds produce a good solution, this experiment is stored in each variable memory, and the possibility of producing a good solution is increased in the next iteration. The worst solutions (worst harmonies) are discarded throughout the procedure and are replaced by others of better quality for each test or iteration, according to the ranking of the solutions. This procedure is repeated until a perfect harmony is found by adjusting the HM's consideration rate and the rate of sound and BW adjustment continuously.

Similarly, when each decision variable chooses a value in the HS algorithm or in the creation of a new solution vector, it follows one of three rules: choose any HS memory value (defined as memory considerations), choose a value close to a value of the HS memory (defined as sound settings), and/or choose a completely random value from the possible range of values (defined as randomness).

In the present work, two important modifications on original HS were adopted. The first, called *Improved Harmony Search*, or HIS, considers the inclusion of the dynamic variation of parameters PAR and bw (Mahdavi *et al.* 2007). The second, named *Modified Improved Harmony Search*, or MIHS (Medeiros and Kripka 2017), allows the reinitialization of the Harmony Memory (aiming to avoid premature convergence to a local minimum), and the inclusion of one predefined solution in the Harmony Memory. As an additional stopping criterion to original HS, the algorithm finishes the optimization process when the best solution found does not vary after successive reinitializations.

2. Formulation and implementation of the optimization problem

2.1 Initial considerations

The formulation of the optimization problem of a composite steel–concrete beam subjected to bending is presented in order to obtain a steel–concrete set of lower cost that simultaneously meets the functionality and safety criteria.

In mixed simply supported beams of steel and concrete the steel component is a solid profile I, with the slab located on the upper face of that profile I. The continuous and semi-continuous composite beams, in which the steel component is a lattice or the slab does not lie on the steel profile, are less frequent cases in practice, which justifies the choice of simply supported beams in this study. In addition, the use of simply supported mixed beams, in the case of typical buildings, makes it possible to obtain a lighter steel profile and with a smaller cross section height when compared to conventional steel beams.

The types of connectors used for mechanical connection are stud bolts. Still, it was considered non-anchored construction.

The formulation aimed at the optimization of composite steel–concrete beams follows the normative requirements for mixed structures of steel and concrete of buildings of the Brazilian Standard ABNT NBR 8800 (2008), regarding the constraints for the limit states, as well as normative recommendations of ABNT NBR 5884 (2013), referring to the standardized relationships between cross-sectional dimensions for Beam-type welded profiles.

The optimization formulation problem was based on the consideration of input parameters related to the characteristics and unit costs of the materials and the stresses acting on the structural element, presented by:

L_b: distance between two sections contained in lateral buckling with a twist (unlocked length);
L_e: beam span;
E_a: steel elasticity module;
E_c: concrete elasticity module;
e_1: distance between the center line of the analyzed beam and the center line of the adjacent beam;
f_{ck}: concrete strength;
f_{ucs}: breaking strength of the connector steel;
f_y: steel flow limit;
q_{ac}: active load before curing;
q_{dc} active load after curing;
C_c: cost of concrete volume;
C_s: cost related to the steel mass.

2.2 Problem variables

The variables of the problem (x_i) represent the cross-sectional dimensions of the steel profile. There are six different variables for the optimization problem, which can be kept fixed at any point in the process. These variables are presented in Fig. 2.

x_1: represents the top table thickness (t_{fs});
x_2: represents the thickness of the lower flange (t_{fi});
x_3: represents the height of the profile (d);
x_4: represents the width of the top flange (b_{fs});
x_5: represents the width of the lower flange (b_{fi});
x_6: represents the thickness of the web (t_w);

2.3 Objective function

The objective function in this study was related to the total cost per linear meter of mixed beam. This cost may be related to both the monetary value of the materials and their environmental impact. The function can be described by the following equation:

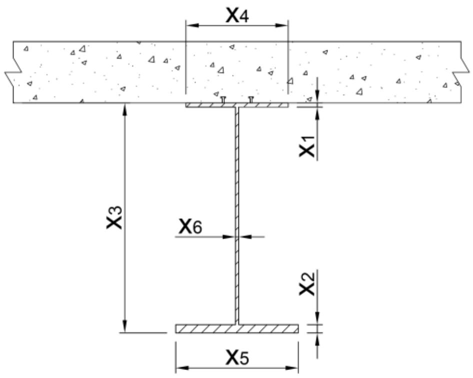


Fig. 2 Design variables for the elements' geometry

Minimize

$$f_{(x)} = P_s C_s + V_c C_c \qquad (1)$$

where the first parcel of the function represents the cost of the steel employed, P_s relates to the amount of material, by mass, considering the specific steel mass adopted as 7850 kg/m³, and C_s is the unit cost of the steel material per unit mass. The second plot represents the concrete cost, where C_c is related to the concrete cost per unit volume, given the characteristic resistance of the concrete used (f_{ck}), and V_c corresponds to the concrete volume used (m³).

The material quantities, P_s and V_c, need to be calculated using the problem variables. In this way, the final formulation of the optimization process f(x) can be described as follows

$$f_{(x)} = [x_1 x_4 + x_2 x_5 + (x_3 - x_2 - x_1)x_6]C_s + (t_c b_{ef})C_c \qquad (2)$$

2.4 Problem constraints

The constraints imposed on the problem refer to the requirements of the current performance standard so that the solutions obtained are applicable in practice. Basically, the constraints in this problem refer to criteria of resistance, deformations, and constructive and manufacturing aspects.

The constraints of the problem are presented in the normalized form, as follows

$$g_1 = 1 - \frac{V_{Rd}}{V_{Sd}} \leq 0 \qquad (3)$$

$$g_2 = 1 - \frac{M_{Rd}}{M_{Sd}} \leq 0 \qquad (4)$$

$$g_3 = 1 - \frac{\delta_{adm}}{\delta_{máx}} \leq 0 \qquad (5)$$

$$g_4 = 1 - \frac{d}{1{,}5 b_{fi}} = 1 - \frac{x_3}{1{,}5 x_5} \leq 0 \qquad (6)$$

$$g_5 = 1 - \frac{t_f}{t_w} \leq 0 \qquad (7)$$

$$g_6 = 5{,}70\sqrt{\frac{E}{f_y}} - \frac{h_c}{t_w} = 1 - 5{,}70\sqrt{\frac{E}{f_y}}\frac{x_6}{h_c} \leq 0 \quad (8)$$

$$g_7 = 1 - \frac{\alpha_{min}}{0{,}40} \leq 0 \quad (9)$$

$$g_8 = 1 - \frac{1}{\sigma} \leq 0 \quad (10)$$

$$g_9 = 1 - \frac{\alpha_y}{1/9} \leq 0 \quad (11)$$

$$g_{10} = 1 - \frac{9}{\alpha_y} \leq 0 \quad (12)$$

Regarding the resistance criteria, the main constraints imposed on the optimization problem relate to the soliciting forces and the resistive strength of the section, so that the MSd bending moments and the V_{Sd} shear forces have values less than or equal to the shear moments and shear forces and the maximum arrow (δ_{max}) is less than or equal to the permissible displacement(δ_{adm}), as shown in Eqs. (3) to (5), respectively. With regard to manufacturing restrictions referring to the recommendations of the standards used for standard welded profiles, we have Eq. (6), which limits the profile height ratio (d) over the width of the lower flange (b_{fi}), greater than 1.5 and Eq. (7), which defines the thickness of the web as less than or equal to the thicknesses of the flanges. Restriction 6 (Eq. (8)) requires that the ultimate limit condition does not contemplate cross-sectional configurations that fit into slender web beams. Constraint 7 (Eq. (9)) holds that the degree of minimum interaction (α_{min}) between the elements (concrete slab and steel profile) so that the beam can be dimensioned as a mixed element, must not be less than 0.40, which means 40% of interaction. Meanwhile the maximum degree of interaction, α, cannot be greater than 1, as this value already indicates the total interaction between the elements (Eq. (10)).

If any restrictions are not met, the objective function is penalized. This procedure is performed by adding a penalty function P(x) to the objective function f(x), where F(x) is the penalty function (Eq. (13)). The penalty function P(x) is calculated by Eq. (14), where g(x) corresponds to the value of each of the unreserved constraints, and r is the penalty factor, adopted in the present work as equal to 1000.

$$F(x) = f(x) + P(x) \quad (13)$$

$$P(x) = \sum_{i=1}^{m} r.\,g_i(x) \quad (14)$$

In addition, the lateral constraints of the problem must be met, related to the interval at which the problem variables must be contained. These limits were based on what Brazilian steelmakers offer in terms of the types of materials, thicknesses, and dimensions of flat plates applied in the manufacture of welded steel "I" profiles.

Due to the limitations in the welding process, there are some restrictions on the dimensions of the welded I profiles, including the minimum dimensions (lower limits) for the width of the flange bf being equal to 100 mm and 150 mm for the height (d) of the section of the profile. The upper limits for the width of the bf flange and height of the d profile were considered equal to 2000 mm, due to the width of plates standardized by the mills.

The thicknesses of the flange tf and the web tw are within the validity range of the variables due to the limitations of the manufacturing process. Thus, the minimum thickness for the flange and the web is 4.75 mm; hence, these are the lower limits. For the upper limits, the thickness of 50 mm was adopted for the table, and for the soul, some intermediate thicknesses were considered.

Accordingly, the variables can assume values of the exposed sets

x_1e x_2 [4.75;6.35;8.0;9.5;12.5;16.0;19.0;22.4;25.0;28.5; 31.5;37.5;44.5;50.0], in mm (15)

x_3 ∈[150;...;2000], in mm (16)

x_4 e x_5∈[100;...;2000], in mm (17)

x_6 ∈[4.75;6.35;8.0;9.5;12.5;16.0;19.0;22.4;25.0;28.5; 31.5;37.5;44.5;50.0], in mm (18)

3. Numerical applications

3.1 Introduction

In order to obtain optimized sections of composite steel–concrete beams, an optimization routine was developed. In addition, the resistant capacity of sections was verified based on the normative requirements (ABNT NBR 8800, 2008) using a programming algorithm in Fortran language.

For validation of the proposed formulation and the optimization method used, numerical applications were developed referring to cost optimization. A comparison between the optimization of monetary costs and environmental costs of sections of mixed concrete beams is presented, based on values from the environmental scoring literature for each input used. Finally, a comparison between the costs of a steel beam and a mixed steel–concrete beam, both optimized, is presented to analyze the potential strengths of both structures and their costs.

The results presented were the best obtained for 10 independent runs, each run needing about 180s on a computer with Intel Core i7 CPU @ 2.4 GHz and 8GB of RAM. The maximum number of function evaluations NI (improvisations) was set to one million. The optimization process is finished when NI was achieved, or after three reinitializations without any improvement.

3.2 Optimization of monetary costs

This example deals with a mixed beam configuration, which has been pre-dimensioned for a span of 17.5 meters and refers to a secondary beam belonging to the floor of a commercial building deposit. The geometry of the mixed

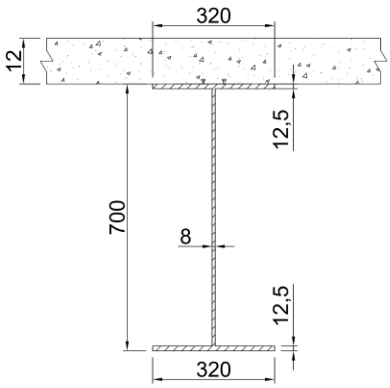


Fig. 3 Dimensions proposed for the reference section

beam consists of a profile of welded steel of VS 700x115 series and a solid concrete slab with a thickness of 12 cm, non-anchored construction, and interaction varying for the different analyses; the incorporation of steel formwork was not considered. The dimensions of the cross-section in question are shown in Fig. 3, with the steel profile in mm and the thickness of the concrete slab in cm.

The characteristics and properties of the materials that were used in the mixed beam model under analysis are listed below:

- Beam span (L_e): 17.50 m, without lateral locking;
- Distance between the center line of the analyzer beam and the center line of the adjacent beam (e_1): 2.50 m;
- Concrete strength (f_{ck}) of 25 Mpa, concrete elasticity module (E_c) equal to 2415 kN/cm² and consideration of large aggregate of gneiss;
- Type of steel adopted: Steel ASTM A-572 Gr. 50, with elasticity module, E, equal to 20000 kN/cm²;
- Specific steel mass: 7850 kg / m³;
- Tensile strength of the connector steel (f_{ucs}): 41.5 kN/cm²;
- Nominal connector diameter (d_{cs}): 19 mm;
- The cross-sectional area of the connector shaft (A_{cs}): 2.84 cm²;
- Connector group: 1;
- Modification factor for non-uniform bending moment diagram (C_b): 1.136;
- The coefficient of adjustment for the consideration of the effect of groups and connectors (R_g): 1.0;
- The coefficient for consideration of the connector position (R_p): 1.0;
- The coefficient of buckling of the shear core (k_v): 5.0;
- It was not considered a built-in steel mold.

As permanent actions, before and after the curing of the concrete with its characteristic values, the weights of the concrete slab and steel beam were adopted, including a load of 0.5 kN/m², referring to the weight of the connectors and other elements of the steel profile. The weights were determined automatically taking into account the steel and concrete sections obtained in each iteration as well as those updated automatically. The specific weight of the steel section was determined by the product of the specific weight of the steel (γ = 78.5 kN/m³) and the section steel area (m²). Likewise, for the specific weight of the concrete slab, where the concrete weight (γconc) of 25 kN/m³ was multiplied by the thickness of the concrete slab (t_c in m) and by the distance between the center line of the analyzed beam and the center line of the adjacent beam (e_1 in m). As variable actions, a construction overload of 1.0 kN/m² (before concrete curing) and a total variable action of 1.5 kN/m² (after concrete curing) were considered for use and occupation, according to prescriptions of NBR 6120 (ABNT, 2000).

The values of the stock weighting coefficients used in the example were based on item 4.7.6.2.2 of NBR 8800 (ABNT 2008). For concrete combinations, during the construction and before concrete curing the stock weight coefficient adopted for the weight of the steel profile and connectors was γ_g = 1.15; the concrete weight of the concrete slab was γ_g = 1.25, and for the variable action, γ_q = 1.30. For the serviceability load combination after curing the concrete, the stock weighting coefficient for the own weight of the steel profile and connectors was equal to γ_g = 1.25, the concrete weight of the concrete slab was γ_g = 1.35, and for the variable action, γ_q = 1.50.

For the unit costs of the materials (Table 1), the unit value of the cost of the steel C_s used the thick steel plate ASTM A572 Degree 50 as a reference (350 MPa). Meanwhile, the unit cost of concrete, C_c, in R$/m³, was included for protection against cracking, with a welded steel mesh CA-60, 10 x 10 cm mesh spacing, 4.2 mm wire diameter, and a width of 1 m.

As aforementioned, the optimization routine was performed 10 times for each analyzed case, selecting the mixed steel–concrete beam configuration corresponding to the lowest cost.

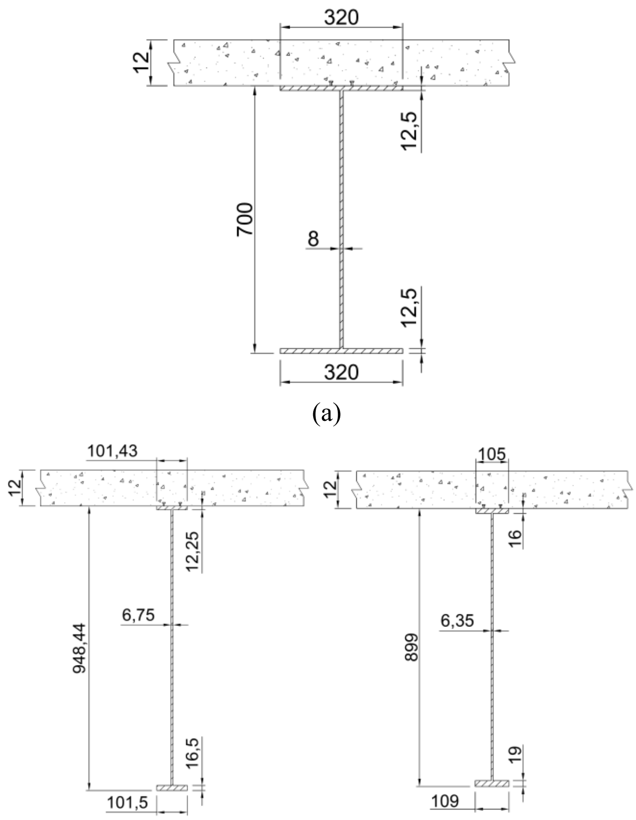
3.2.1 Case I

Based on the mixed beam configuration used as a reference section, for the purpose of analyzing the influence of the values obtained for each variable, continuous variables were considered in the optimization, and secondly, discrete variables. The discrete variables assume multiple values of a millimeter for the steel profile, considering its lower and upper limits, which were defined solely according to the standards of commercially available steel plates, as previously presented. From the series of tests, the cross-sections were chosen that obtained the best cost for both cases, as indicated in Table 2 and in Fig. 4. A partial interaction of 40% was considered for the analyses.

The steel consumptions of the profiles suffered a reduction of 31.90% and 31.06%, considering the continuous and discrete variables, respectively, when compared with the steel consumption of the reference profile.

Table 1 Unit costs of the materials used in the study

Cs (R$/kg) 350 MPa	Cc (R$/m³) 25 MPa
6.80	365.00



(a)

(b) Continuous variables (c) Discrete variables

Fig. 4 (a) Reference section and optimized section considering (b) continuous variables and (c) discrete variables

Table 2 Comparison between discrete variables and continuous variables considering a span of 17.5 meters

	d (mm)	t_w (mm)	b_{fs} (mm)	t_{fs} (mm)	b_{fi} (mm)	t_f (mm)	t_c (cm)	R$/m
Reference Section (Steel profile VSM 450 x 59)	700.00	8.00	320.00	12.50	320.00	12.50	105.19	726.24
Optimized Section (Continuous variables)	948.44	6.75	101.43	12.25	101.5	16.50	71.63	498.08
Optimized Section (Discrete variables)	899.00	6.35	105.00	16.00	109.00	19.00	72.51	504.04

The costs of the mixed section were reduced by approximately 31.42% for the optimized section considering continuous variables and 30.59% for the optimized section considering discrete variables, which represents a small and insignificant difference considering the two natures of the variables. Considering the feasibility of construction, only discrete variables were adopted in the other analyses in the present study.

Table 3 Dimensions and costs of optimized cross-sectio

Span	d (mm)	t_w (mm)	b_{fs} (mm)	t_{fs} (mm)	b_{fi} (mm)	t_{fi} (mm)	R$/m
5	272	4.75	100	4.75	100	4.75	272
7,5	449	4.75	100	4.75	100	4.75	449
10	633	4.75	100	4.75	101	4.75	633
12,5	742	6.35	100	6.35	102	6.35	742
15	881	6.35	103	8	106	8	881
17,5	899	6.35	105	16	109	19	899

It should be noted that, for the case in question, the discrete variables result in a combinatorial problem with approximately $1.14\text{x}10^{10}$ solutions, considering the limits for each variable. In light of this, it is difficult to obtain a good solution to the problem without the aid of some optimization method.

3.2.2 Case II

The solutions optimized for the different spans adopted are presented. Table 3 presents the results obtained for the steel profile dimensions, expressed in mm, the thickness of the solid concrete slab (cm) for the optimized cross-sections, as well as the costs of the cross-sections as a function of the variation in the spans, considering the minimum interaction between steel–concrete elements (40%).

The slenderness of the web can be observed, with no gap from the starting section to the span of 10 meters, as the optimization algorithm adopted the minimum value specified for the thicknesses of commercial plates. This fact can be explained by the reference section adopted. In this way, the algorithm changed the dimensions of the optimized section from the starting section, initially fixing the slenderness of the web to its limit lower (4.75 mm). This logic was maintained during the iterations since there is a tendency of the optimization algorithm to reduce the thickness of the web and increase its height, resulting in an increase in the inertia of the section and consequently greater resistance.

With the increase of the effective span, the web can become slimmer due to the need for greater inertia to withstand greater bending requests. However, profiles with slender souls often require constructive details and additional elements, such as stiffeners, in order to control the local instability of the web, which adds value to the final cost.

Thus, the use of thicker webs, as was the case with the solutions obtained for the span equal to and greater than 12.5 m, does not require the placement of rigging and other devices, which despite the higher consumption of steel, promotes productivity gains and labor cost savings. Moreover, in order to reduce the height of the profile or reduce the thickness of the core, such decreases can be compensated by the increase of the table area, as is the case for the configurations generated for spans of 12.5 m and above.

Table 4 Comparison of slenderness and optimum relation of mixed elements

Span (m)	d (mm)	L/h	d/b_{fi}
5	272	18.38	2.72
7.5	449	16.70	4.49
10	633	15.79	6.27
12.5	742	16.85	7.27
15	881	17.03	8.31
17.5	899	19.46	8.25

Table 5ULS verification related to displacement

Span	δ_{adm}	δ	$\Delta\delta$ (%)
5	1.43	1.43	0
7.5	2.14	2.14	0
10	2.86	2.85	-0.35
12.5	3.57	3.57	0
15	4.29	4.28	-0.23
17.5	5.00	5.00	0

In order to compare the slenderness of the mixed elements of steel–concrete, the parameter L/h was used, where h is the total height of the profile, (in this work, called d). This relationship is presented in Table 4, which shows the result of the relation d/bfi, referring to restriction 4, defined according to the prescription of NBR 8800 (ABNT, 2008).

In the case of steel–concrete composite beams, particularly in terms of the steel profile, bending resistance efficiency increases the height of the section, which promotes the increase of inertia. The solution for I profiles is to move the tables away; however, it is necessary to maintain a width x thickness ratio of the core in order to avoid problems of instability (local buckling of the web).

Typical values for the pre-sizing of steel beams for floors are between the Span/20 to Span/25 ratios. The optimized solutions resulted in an average relation of Span/17.37.

As for the optimum relation for welded I profiles subjected to bending stress, d/bfi, presented in NBR 5884 (ABNT, 2013), in general, sections that have relations inferior or close to 1.5 have tables with widths and thicknesses that are considered large. However, with d/bfi ratios greater than 4.0, the tables are reduced in proportion to the core, which has a larger thickness, so there is an increase in the cross-sectional steel area, and consequently, an increase in the final cost. For the cases with less thick web, it is important to be aware of the localized effects in the web (local buckling of the web).

Table 5 shows the Ultimate Limit State (ULS) related to the limit displacement obtained for the optimized sections as a function of the variation of the spans, where the maximum displacement (δ) and the allowable displacement (δ_{adm}) are expressed in cm and the spans in m. A $\Delta\delta$ ratio is also shown, which expresses the difference between the maximum and the permissible displacements as a percentage. The displacement constraint was a determinant in the dimensioning of the elements.

3.2.3 Case III

In order to analyze the influence of the degree of steel–concrete interaction, analyses were performed considering total and partial interactions of the element under analysis due to the variation in spans, always aiming to achieve the ultimate limit state and usage. As with the previous analysis, the costs of the shear connectors and the manpower for the installation of these components were not considered. In this last analysis, in addition to meeting the requirements of the standard, we sought to compare the relationships between the gap and the consumption of the beams obtained, the cost versus steel ratio, according to the different degrees of interaction adopted, as well as the number of connectors versus cost.

Tables 6 and 7 show the results obtained for the different spans compared to the interactions between steel–concrete elements in terms of steel consumption and the cost of optimized solutions, respectively. The interactions between the steel–concrete elements varied from the minimum required interaction (40%) to the maximum allowed (100%).

Table 8 presents an analysis considering the influence of the number of shear connectors on the final cost of the mixed beam, adopting a span of 17.50 m and starting from the minimum number of connectors required to meet the

Table 6 Comparison between steel consumption (kg/m linear) in the function of the span for the different degrees of interaction

	Degree of steel-concrete interaction						
Span (m)	40%	50%	60%	70%	80%	90%	100%
5	17.25	17.25	17.25	17.25	17.25	17.25	17.25
7.5	23.85	23.88	23.88	23.88	23.88	23.88	23.88
10	30.74	30.74	30.78	30.78	30.78	30.78	30.78
12.5	46.42	49.81	43.71	43.89	44.53	43.96	43.96
15	56.24	56.37	61.05	56.43	56.49	56.59	56.56
17.5	72.51	72.70	72.71	72.85	72.85	72.85	72.90

Table 7 Comparison of costs (R$/m) as a function of the gap for the different degrees of interaction

	Degree of steel–concrete interaction						
Span (m)	40%	50%	60%	70%	80%	90%	100%
5	122.74	122.74	122.74	122.74	122.74	122.74	122.74
7,5	170.36	170.61	170.61	170.61	170.61	170.61	170.61
10	220.01	220.00	220.26	220.26	220.26	220.26	220.26
12.5	326.62	308.87	308.20	309.38	313.72	309.89	309.89
15	393.40	394.26	426.06	394.68	395.11	395.77	395.54
17.5	504.04	505.30	505.38	506.32	506.32	506.32	506.66

resistance requirements for the case in question (28 connectors). The labor for installing the connectors and their unit cost was not considered.

Considering only the number of connectors and partial interaction used in conventional buildings, it was verified that the influence of the same amounts does not result in a significant variation in the final cost of the cross-section. However, for a more conclusive analysis, the cost of labor and the equipment used to install the connectors should be considered.

3.3 Optimizing environmental costs

In the sequence, an analysis is presented aiming at minimizing the environmental costs of the steel–concrete composite beams. Carbon dioxide (CO_2) emission was used as the cost. According to several researchers, this is a parameter that is representative of the material inputs used in the construction of a building, and it is one of the most used parameters for surveying and analysis in studies on the minimization of environmental impacts (Payá-Zaforteza *et al*. 2009, Yepes *et al*. 2012).

In this case, the environmental cost of the proposed solution, as well as the monetary cost, were identified considering a beam span of 17.50 meters. The unit environmental cost and the monetary cost used for the materials are presented in Table 9. The costs in terms of kg of CO_2 emitted per m^3 of concrete were taken from the work of García-Segura and Yepes (2016), referring to the database from the Institute of Construction Technology of Catalonia, while the amount of kg of CO_2 emitted per kg of steel was extracted from the work of Gilbert *et al*. (2017), based on the database of the World Steel Association.

The results obtained for this case are presented in Table 10, with the steel sections of the profile expressed in cm^2 and the material costs of the beam expressed in linear R$/m (monetary cost) and in kg of CO_2 emission (environmental cost) for both solutions obtained. Fig. 5 shows the optimized sections obtained for each evaluated cost nature, while Fig. 5(a) shows the section with the minimum monetary cost and that with the lower environmental cost. The dimensions of the steel profile are given in mm and the thickness of the concrete slab in cm.

Table 8 Number of connectors versus cost ratio

Number of connectors	Cost ratio (R$/m)
24	504.18
26	503.15
28	504.04
30	502.81
32	504.33
34	504.62

Table 9 Unit costs of the materials used in the study

Material	Monetary Costs (R$)	Environmental Costs CO_2 (kg)
Concrete 25 Mpa (m^3)	365.00	321.92
Steel (kg)	6.80	1.116

Table 10 Total costs of optimized solutions

	Total Cost
Monetary Solution (R$/m)	504.04
Environmental Solution (kg/CO_2)	90.96

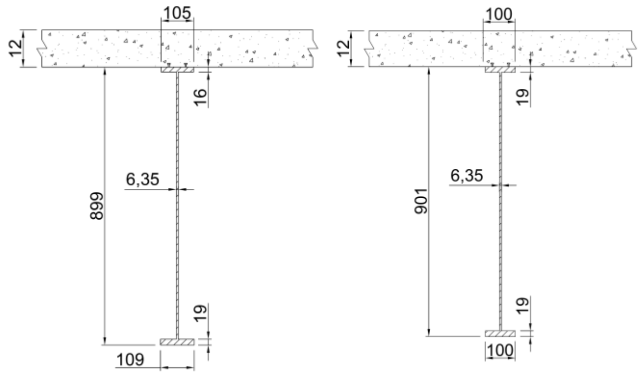


Fig. 5 Monetary optimized solution (a) and optimized environmental solution (b)

The result obtained for the environmental optimization was very similar to the one obtained for the monetary solution, with small differences in the dimensions of the cross-section but similar consumption of steel and concrete. The achievement of similar configurations as shown in Figs. 5(a) and 5(b) is a trend that was recognized in the works of Payá-Zaforteza *et al*. (2009), Yepes *et al*. (2012), and Medeiros and Kripka (2014). Considering the optimized monetary solution, it can be inferred that with a small increase in cost (0.45%), the best possible solution from an environmental point of view is obtained. Considering this, it is possible to say that the structures optimized considering the monetary cost, due to the rationalization of the consumption of materials, are directly related to the reduction of the environmental impact.

3.4 Cost-optimization steel beam versus steel-concrete mixed beam

In the sequence, the steel consumption and the resistant capacity are presented to compare the bending moment and the final cost obtained from the optimization of steel–concrete composite beams and steel beams. For the comparatives, we used the optimized results related to the mixed beams presented in the optimization of the monetary costs of this work. The cross-sections of steel beams and composite beams were also checked in accordance with Brazilian standards NBR 8800 (ABNT, 2008) and NBR

5884 (ABNT, 2013). The comparative analyses considered a 40% interaction between the steel–concrete elements of the mixed beams and an unlocked length of zero for the steel beams. The values obtained for the steel consumption of the sections (kg/m) as well as for the final cost per linear meter of a beam (R$/m) for steel elements and mixed steel–concrete elements, considering variations in spans, are shown in Figs. 6 and 7, respectively. In the cost of the steel profile per linear meter, the value of the 12 centimeters thick concrete slab was added.

Fig. 6 shows the difference in the reduction of steel consumption and the final cost of the section per linear meter when the mixed behavior for the beams of building floor systems is provided. As the free space is increased, there is a need for profiles with greater inertia, that is, more resistant to limit the displacements, which explains the most significant differences in the steel consumption between the elements for the larger spans.

The constructional typology adopted for the mixed beams of this study, non-anchored constructions, results in higher displacement values during the construction phase, during which the isolated steel profile must support the permanent loads alone. For this type of constructive typology, such displacements during construction (δ_1), in most cases, are the determinants in the design and verification of these elements.

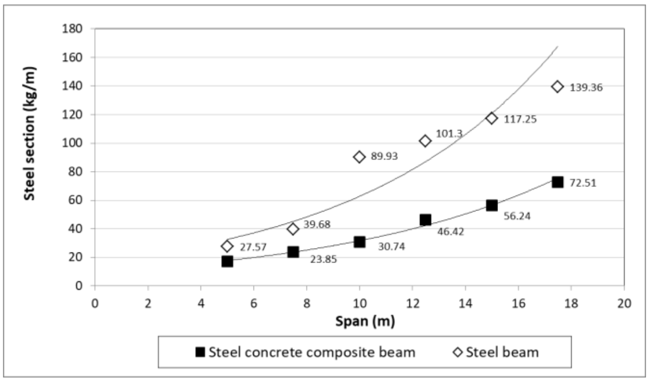


Fig. 6 Comparison between steel consumption for steel–concrete composite beams and steel beams

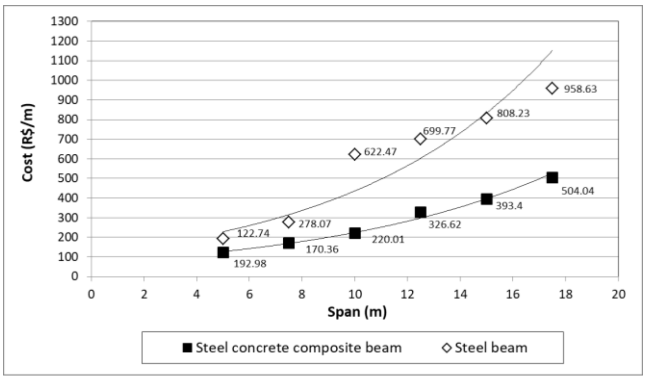


Fig. 7 Comparative between the cost of steel–concrete mixed beams and steel beams

Table 11 Percentages of reduction in steel consumption and in the cost per linear meter of mixed versus steel beams

Span (m)	Reduction in the steel consumption of sections (%)	Reduced cost of sections (%)
5	37.43	36.40
7.5	39.89	38.73
10	65.82	64.65
12.5	54.17	53.32
15	52.03	51.32
17.5	47.97	47.42

For mixed beams and isolated profiles, the displacements were determinant in the dimensioning of the sections. If the mixed beam had been dimensioned considering only the ELU in the bending, that is, to deactivate the displacement constraint, there would have been a greater difference between the consumption of steel for the steel and mixed elements, since there would not be a a considerable difference between demanding and resistant moments.

A summary of the percentage differences in steel consumption and cost per linear meter of composite versus steel beams is presented in Table 11.

As can be seen, the reduction in the steel consumption of the sections in kg per linear meter of beam reached 65.82% for the span of 10 meters (i.e., more than half of the consumption was reduced). Likewise, the cost per linear meter for the section of mixed beam with a span of 10 meters reached a 64.65% reduction when compared to the section of isolated steel beam, which shows that the option for the mixed system proved to be more advantageous for floor beams since, due to the reduction in steel consumption for composite beams, the final cost was also reduced. Hence, it can be concluded that for such a mixed beam configuration, the ideal span is around 10 meters. Table 12 shows the results obtained for the dimensioning of steel beams and steel–concrete composite beams related to the resistant-bending moment.

Table 12 Results obtained for the resistant-bending moment of the steel and mixed sections

Span (m)	Resistant moment steel beam (kN.m)	Resistant moment steel–concrete beam (kN.m)	Increased resistance steel beam–mixed beam (%)
5	52.36	123.01	134.93
7.5	118.85	181.70	52.88
10	219.17	295.69	34.91
12.5	344.28	491.23	42.68
15	501.70	694.36	29.43
17.5	692.33	1033.43	49.27

Clearly, increased strength is one of the advantages of using composite beams. By comparing the resistant-bending moment of the two elements, it can be seen that the mixed beam is more efficient, since, as a result of the loads acting on the structure, significantly stronger bending moments are obtained for the steel–concrete composite beam than for the steel beams, reaching an increase of 134.93% in the bending moment resistant to the span less than 5 meters.

Due to the combination of the concrete slab with the steel profile, even if it is of minimal thickness, the contribution of the slab makes it possible to reduce the consumption of steel and consequently the final cost of the mixed beam per linear meter while improving the resistant capacity of the mixed element. This is because the mixed beam resists a relatively greater bending moment, as the concrete slab provides lateral locking, preventing the structure from suffering lateral buckling by twisting. This is an advantage when compared to the isolated steel beam, which usually isnot locked.

4. Conclusions

This work proposed the minimization of the monetary and environmental costs of sections of steel–concrete composite beams, submitted to bending, through the HS optimization heuristic process. The Brazilian ABNT NBR 8800/2008 regulation was used to verify the resistant capacity of the sections. In addition, the considerations of the NBR 5884 regulation of welded profiles (ABNT, 2013) were also evaluated.

To do this, a formulation was developed for the optimization problem. A series of numerical applications was developed for the validation of the proposed formulation, and the HS method was used as an optimization method.

In the optimization of the monetary costs of mixed steel–concrete sections, the cost of optimized solutions, whether working with discrete or non-continuous variables, did not increase significantly. Thus, with respect to the production feasibility of the parts, it is not advantageous to adopt continuous variables for the optimization because, with discrete variables, the solution set adopted for the thicknesses of the plates corresponds to the commercially sold dimensions. Thus, the optimized steel profiles could be easily made.

Regarding the influence of cross-section dimensions varying the spans of the pieces, there was a tendency of the optimization algorithm to generate solutions where the thickness of the web was reduced and the height increased, https://doi.org/10.1007/s00158-013-0897-6while the tables were thicker and had a greater width to guarantee an increase in the inertia of the section and, consequently, better resistant capacity as well as material savings.

As for the analysis of the influence of the degree of interaction and the number of connectors in the design of steel–concrete composite beams, in general, the monetary cost was little influenced by the degree of interaction between the steel–concrete elements. In typical commercial building conditions, reducing the degree of interaction could be an advantage, as it reduces material costs and the need for specialized manpower for the installation of the shear connectors. Additionally, the influence of the number of connectors did not result in significant variation in the final cross-sectional cost; however, it should be noted that the final cost, the installation labor, and the unit cost of the shear connectors were not recorded.

The optimization of environmental costs was carried out for the same reference section used in the optimization of monetary costs, referencing environmental scoring values for each input used in steel–concrete mixed beams taken from the literature. The result of the monetary optimization was very similar to the one obtained by the environmental solution, a tendency that has been shown in the literature. It can be concluded that the optimization of monetary costs, due to the rationalization of the consumption of materials, is directly related to the reduction of environmental costs.

Finally, the comparison between the optimized solutions of steel–concrete composite beams and steel beams allowed us to conclude that the contribution of the slab in the composite steel–concrete beams results in better strength and a lower final cost compared to isolated steel beams. The advantage of composite beams lies in the locking provided by the concrete slab, which makes it possible to prevent from the instabilities that can reduce the resistance of the part. This results in economic advantages through the adoption of smaller steel profiles. As non-anchored construction was adopted for steel–concrete composite beams, the maximum displacements were the limiting factors in the dimensioning of the mixed elements.

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