Multi-Objective Harmony Search applied to minimize cost and displacement of steel-concrete composite beams

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Abstract. During the design of structures, it is common for the engineer to come across situations in which different and conflicting objectives must be assessed, where the multi-objective or multicriteria optimization provides subsidies to assist in decision-making by designers. In this sense, this paper aims to present the cost and displacement minimization of steel-concrete composite beams, applying the Multi-objective Harmony Search (MOHS) algorithm. The steel-concrete beam is represented by nine design variables, namely the concrete strength of the slab, the slab thickness, the dimensions of the welded steel beam, and the interaction degree. Solutions are verified in terms of ultimate and serviceability limit states according to Brazilian standards. With the optimization results, a Pareto front is generated, and the efficiency of the MOHS is evaluated from the comparison with results of another multiobjective optimization algorithm already consolidated in the literature, the Nondominated Sorting Genetic Algorithm II (NSGA-II).

Keywords: Multi-Objective Harmony Search (MOHS), multi-objective optimization, Pareto front, steel-concrete composite structure.

1 Introduction

The composite steel-concrete beams exhibit exceptional structural performance due to the utilization of each material in situations where it performs best, namely steel in tension and concrete in compression. Composite structures have been popular as a solution in several projects due to these properties. More recently, some other advantages of composite structures were mentioned, such as their reduced environmental impact regarding other structural materials [1]. Combining this type of structure with optimization techniques can improve its efficiency even further, as optimization methods have previously proven to be effective instruments for assisting in the design of structures, rationally identifying solutions with lower costs [2].

During the design of structures, the engineer is frequently confronted with scenarios in which conflicting objectives must be considered [3]. In this case, multi-objective optimization can be used as a tool to help in multicriteria decision-making by allowing the examination of trade-offs between each objective. In contrast to single-objective optimization, multi-objective optimization yields a set of non-dominated or Pareto-optimal solutions. A non-dominated solution is one in which no objective can be enhanced without negatively impacting at least one of the other objectives. These solutions are used to compose the Pareto front, which in turn allows analyzing the relations among considered objectives [4].

Harmony Search (HS) is a heuristic optimization method inspired by jazz musical improvisation [5]. According to the analogy, musicians improvise new combinations between instrument notes in search of perfect harmony. In the optimization problem, this relates to creating new values for the variables, seeking the global optimum of the objective function. Although it was originally designed for single-objective problems, there are different proposals to adapt the method to multi-objective problems.

This study aims to carry out multi-objective optimization of composite steel-concrete beams in order to minimize cost and displacements. For this purpose, a Python program was developed using the Multi-Objective Harmony Search (MOHS) method. To assess the trade-offs between the objective functions, a Pareto front formed of the non-dominated solutions produced by the optimization was obtained. To validate the MOHS results, the Pareto front was compared with the results obtained by using a well-established multi-objective genetic algorithm optimization method known as NSGA-II.

2 Multi-Objective Harmony Search (MOHS)

Geem, Kim, and Loganathan [5] presented the original Harmony Search (HS) method, consisting of an algorithm that is analogous to the process of musical improvisation in jazz. Its operation is based on the improvisation of new harmonies (solutions) and memorization, with the best solutions being saved in the harmony memory and the worst being discarded. HS has been used for multiple optimization problems since its publication, and significant modifications to the algorithm have been made, as detailed by Zhang and Geem [6].

Some of the modifications focus on making the method applicable to multi-objective optimization problems while retaining as much of the algorithm's original structure as possible. In this sense, the publication by Ricart *et al*. [7] proposes two algorithms called Multi-objective Harmony Search 1 and 2 (MOHS1 and MOHS2). The main difference between the single-objective algorithm and the multi-objective variants is the use of harmony memory (*HM*), which in the case of MOHS becomes a repository for Pareto-optimal solutions.

Similar to MOHS2, Sivasubramani and Swarup [8] present an algorithm that takes into account the crowding distance and a dynamic variation of the HS adjustment parameters, originally proposed to the mono-objective HS by Mahdavi, Fesanghary and Damangir [9]. The approach makes use of the solution ranking method proposed by Deb et al. [10], aiming for a better conformation of the optimal Pareto front when considering crowding distance by phenotype. Based on the implementation of this method in benchmark multi-objective optimization problems, Molina-Pérez et al. [11] show that the algorithm outperforms the previous variants. Considering these characteristics, this was the MOHS algorithm applied in this research. The implemented algorithm can be described in 5 main steps, as illustrated in the flowchart presented in Fig. 1.

3 Optimization Problem Formulation and Implementation

The problem under consideration is presented by Tormen et al. [12], which consists in optimizing secondary steel-concrete composite beams that compose the floor of a warehouse in a commercial building. The geometry of the composite beams consists of a 12 cm thick concrete slab and a welded I-beam connected by stud bolt shear connectors. The structure is considered to be unpropped and without incorporated steel formwork. With a total span of 17.5 m, the composite beam is simply supported. A spacing of 2.5 m was assumed between the examined beam's axis and the adjacent beams. The beam steel is ASTM A-572 grade 50 with a tensile strength f_y of 350 MPa, and the shear connections have a tensile strength f_{ucs} of 415 MPa. For concrete strength, a value of f_{ck} = 25 MPa was adopted. The values considered for the specific weight of steel and concrete were γ_{steel} = 78.5 kN/m³ and $\gamma_{concrete}$ = 25 kN/m³. Further details regarding the problem are available in the publication.

As illustrated in Fig (2), the height of the steel I-beam (d) is determined later by optimization since it is a function of the studied problem's variables. Figure 3 depicts the design variables examined, which involve the dimensions of the welded I-beam and the interaction degree (α) of the composite beam. In the figure, h_w is the web height, t_w is the web thickness, bf_s is the superior flange width, tf_s is the superior flange thickness, bf_i is the inferior flange width, and tf_i is the inferior flange thickness.

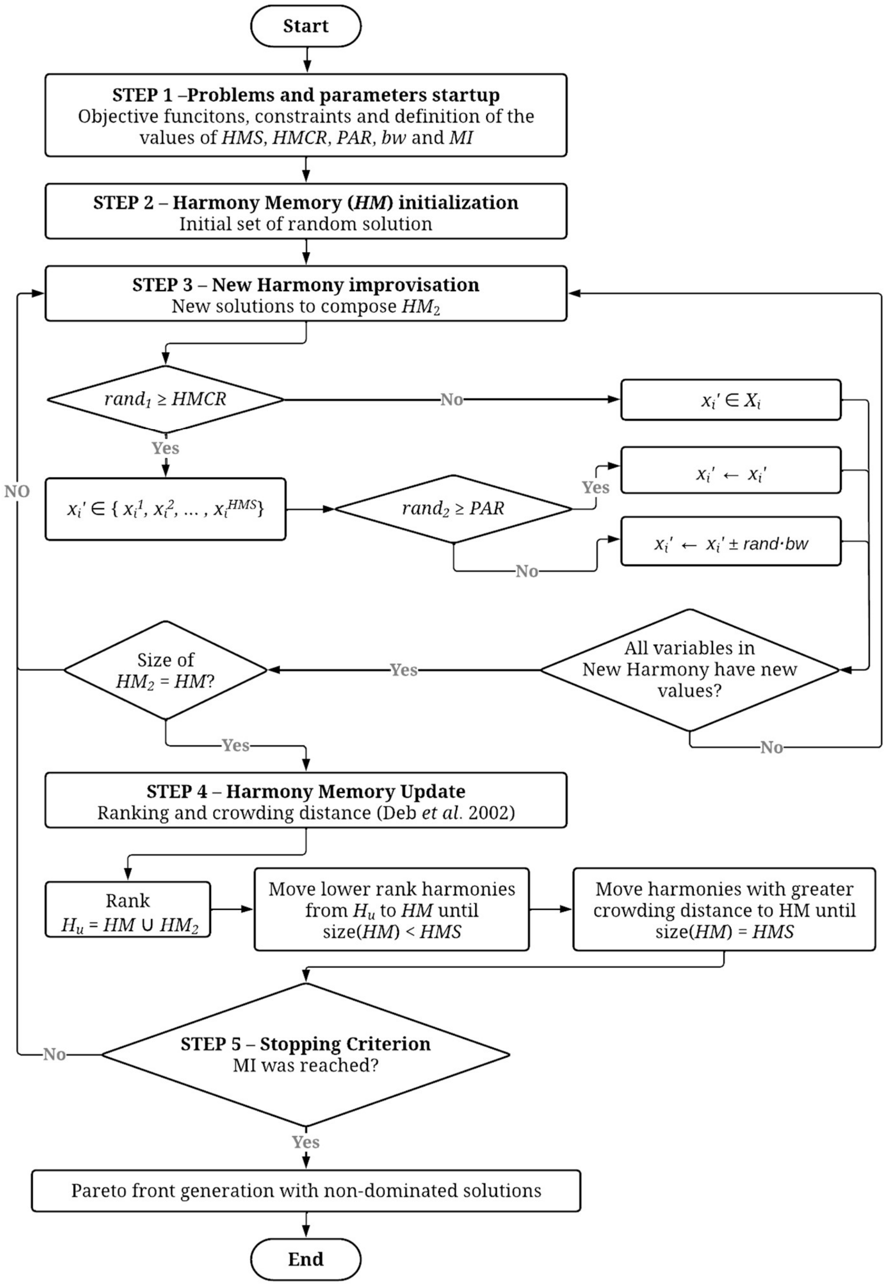

Figure 1. MOHS algorithm flowchart

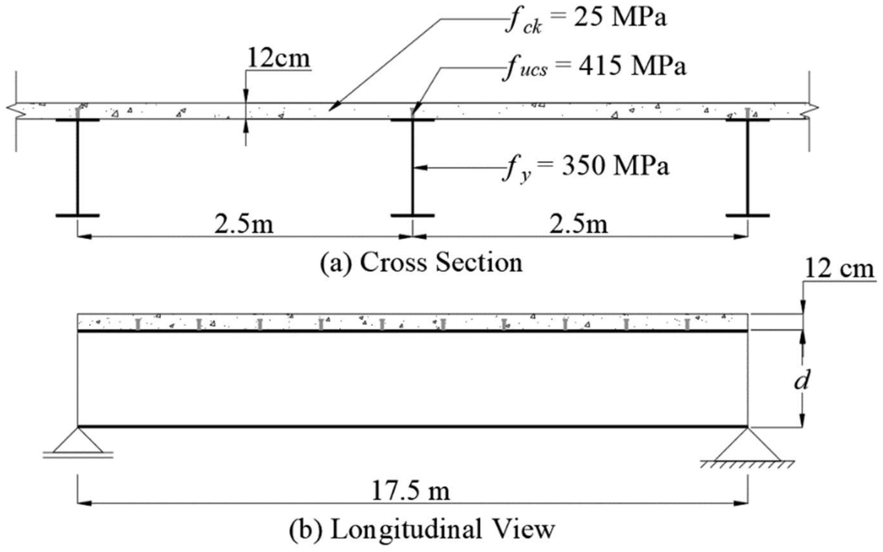

Figure 2. Sections and properties of steel-concrete composite beams

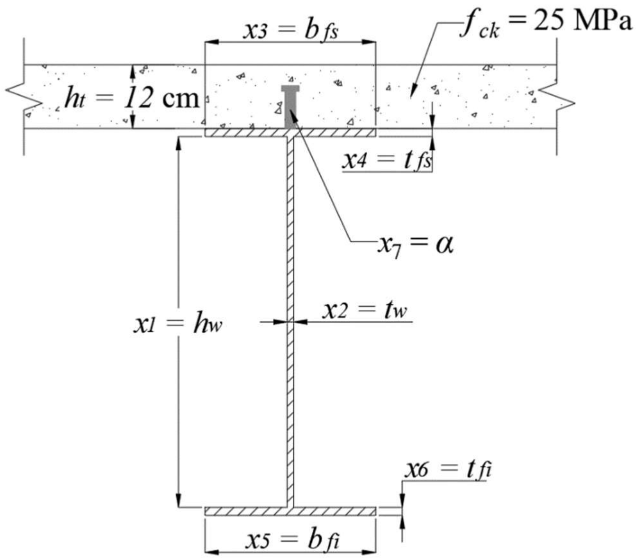

Figure 3. Design variables

The optimization problem in the original research of Tormen et al. [12] is single objective, aiming minimization of the cost of the structure (f_1). This objective can be formulated mathematically using eq. (1):

$$\text{minimize } f_1(x) = C(x) = \sum_{i=1}^{ne} c_i \cdot m_i(x). \quad (1)$$

In eq. (1), the cost of the structure (C) is expressed as a function of the product of the unit cost of each material (x_i) and the corresponding material consumption (m_i). The cost is composed of two elements (ne), being: the volume of concrete, and the mass of steel for the I-beam. Table 1 shows the unit costs of each material, with values taken from the cited publication, in Brazilian currency Reais (R$).

Table 1. Unit costs

Material	Value	Unit
Concrete 25 MPa	365.00	R$/m^3
ASTM A-572 50 Steel grade	6.80	R$/kg

The objective of minimizing structure displacement was included in this study, thereby transforming the problem into a multi-objective one. The total beam deflection (δ_{max}) is determined using Eq. (2), evaluated by the displacement in simply supported beams. In the expression, $\delta_{p,pa}$ is the displacement caused by dead loads before concrete hardening, $\delta_{p,ld}$ is the displacement generated by dead loads after concrete hardening, $\delta_{v,cd}$ is the displacement caused by short-term live loads, and $\delta_{v,ld}$ is the displacement generated by long-term live loads.

$$\text{minimize } f_2(x) = \delta_{max} = \delta_{p,pa} + \delta_{p,ld} + \delta_{v,cd} + \delta_{v,ld}. \tag{2}$$

To address the multi-objective optimization problem, a Python program was developed, which implements the MOHS algorithm previously described. The values of the algorithm's parameters were obtained after several experiments, and are presented in Tab. 2. It is noteworthy that the size of the harmony memory (*HMS*) ends up specifying the number of solutions that can construct the final Pareto front in the case of MOHS. To validate the MOHS results, the NSGA-II method was applied to the same problem to compare the generated Pareto front. An electronic spreadsheet and the SolveXL supplement were utilized for this.

Table 2. MOHS parameters values

Parameter	Value
HMS	20
$HMCR$	0.5
$PAR_{mín}$	0.1
$PAR_{máx}$	0.9
$bw_{mín}$	0.1
$bw_{máx}$	0.5
MI	500,000

The solution must meet the current sizing guidelines in order to be feasible. The structures used in this study are evaluated using the Brazilian technical standards NBR 8800 [13] and NBR 5884 [14]. If a solution fails any of the verifications (or constraints), the solution is penalized. Based on previous experiments, a penalty factor of 10^4 was chosen.

4 Results and Discussion

In this item, the results obtained from the multi-objective optimization of the proposed problem are presented. From the non-dominated solutions obtained with the application of MOHS and NSGA-II, the respective Pareto fronts have been generated, which are compared in Fig. 4. As expected, the objectives considered are conflicting, hence solutions with lower displacements have a greater cost, and vice versa. It is also possible to verify that both multi-objective optimization methods produced a well-shaped Pareto front, with a satisfactory diversification among the solutions.

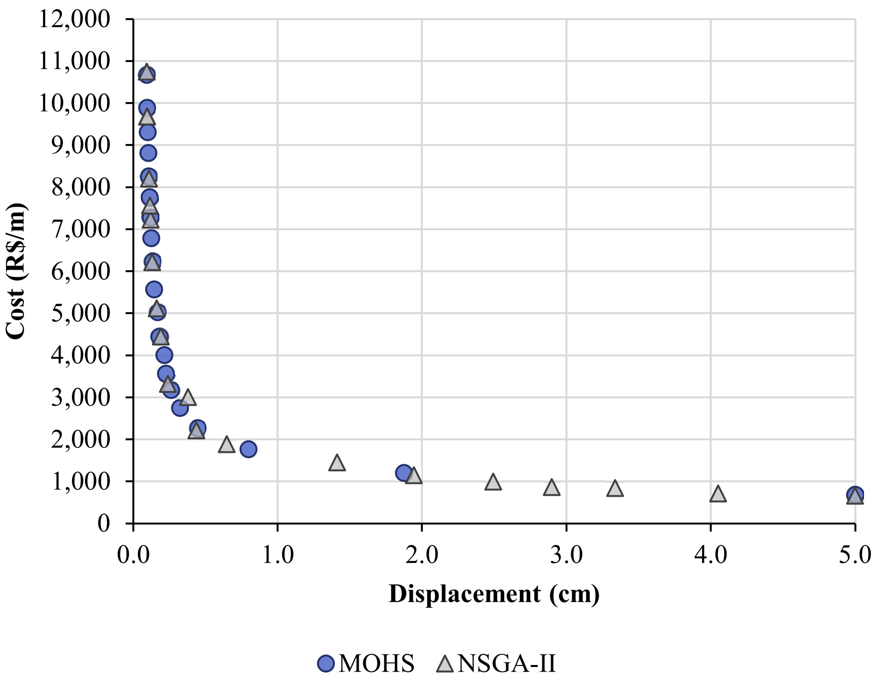

Figure 4. Pareto frontiers obtained with MOHS and NSGA-II

Still, in Fig. 4, it is possible to observe that MOHS was able to discover non-dominated solutions with objective function values very similar to those of NSGA-II, demonstrating that it is an efficient multi-objective optimization algorithm capable of achieving competitive results when compared to established methods. Another important aspect to emphasize is that the most extreme solutions, i.e., those with the lowest cost and displacement, are extremely similar among the algorithms examined. This indicates that MOHS was able to find solutions that were equally effective as those of the NSGA-II when considering the objectives individually.

To the problem studied it can be seen that the NSGA-II results show a wider diversity of solutions for displacements greater than 1 cm, whereas the MOHS concentrates on solutions with different costs and displacements below 0.5 cm. The small number of solutions that compose the Pareto front, as well as the magnitude of displacement values in relation to cost, can partially explain this behavior. Once different computing languages and tools were used, it was not possible to compare NSGA-II and MOHS regarding processing time, although NSGA-II needed a smaller number of function evaluations. Preliminary results indicate the necessity of further calibrations and improvements in the algorithm to generalize the conclusions obtained.

The results of the optimization of the steel-concrete composite beams evidence an exponential increase in the cost of the beams when the displacements are minimized. Notably, the results also reveal that the structure's displacements can be significantly decreased with a minor increase in cost, particularly in the range closest to the 5 cm limit. To reduce the displacement from 5 cm to 4 cm, the structure's cost must be increased by approximately 9% or R$ 60 per meter of the beam. To minimize the displacement to 2 cm, the cost must be raised by 75%. Reductions in displacement greater than 0.5 cm become expressively expensive, with the growing expense for a smaller reduction in displacement, in addition to having minimal practical demand.

5 Conclusions

Based on the presented results, it is possible to conclude that the MOHS algorithm presents competitive results in relation to methods currently established in the literature, such as NSGA-II. Calibration of method parameters, as well as improvements of the method, may be performed to improve the diversity of solutions and the algorithm's performance. Regarding the problem analyzed, it’s evident from the Pareto front that the structure's displacement can be greatly reduced with a relatively insignificant cost increase, particularly for displacements closer to the 5 cm limit. Only solutions with a displacement inferior to 0.5 cm exhibit expressive expenses associated with displacement reduction. Although only two objectives were considered in this paper, the adopted methodology is being expanded to consider other objectives, such as environmental impact and comfort.

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