PARAMETRIC STUDY OF REINFORCED CONCRETE PLANE FRAMES STRUCTURES THROUGH OPTIMIZATION

ESTUDO PARAMÉTRICO DE ESTRUTURAS DE PÓRTICOS PLANOS EM CONCRETO ARMADO ATRAVÉS DA OTIMIZAÇÃO

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Abstract. This work aimed the parametric study and cost optimization of reinforced concrete plane frames. To achieve these objectives, the total cost, composed by the costs of concrete, steel and formworks was minimized by the usage of a modified version of Harmony Search Algorithm. Cross sections dimensions, area of steel and concrete strength of beams and columns were taken as discrete design variables. The constraints related to dimensions and strength were based on the Brazilian standard ABNT NBR 6118 (2007). Some frame structures were analyzed in order to validate the formulation, as well the application of the optimization method. The results were compared to those obtained from the conventional design procedure, in an attempt to identify the influence of factors such as concrete strength, steel ratio and beams/columns costs on the optimal design of reinforced concrete building frames.
Keywords: **b**uilding; frames; optimization; reinforced concrete; structures; Harmony Search

1. INTRODUCTION

Structural analysis and design usually involve both highly complex procedures and a great number of design variables. As a consequence, the solution has to be found iteratively while initial values are set to the variables based mainly on designer's sensitivity and experience. In addition, the number of analysis steps is remarkably increased if optimum values are to be found among all possible alternatives. To mathematically describe the physical response of a structure, extreme function values can be found by using optimization techniques (KRIPKA et al., 2015).

The great development of structural optimization started in 1960, when mathematical programming techniques were used in the minimization of structures weight. From then on, a great diversity of general techniques has been developed and adapted to structural optimization. However, one of the reasons normally attributed to the little application of the optimization techniques to real structural engineering problems consists of the complexity of the mathematic model generated, normally described by non-linear behavior functions and producing a non-convex space of solutions (several points of optimum), problems for which the resolution by traditional mathematical programming methods have proved to be little efficient. For the resolution of these kind of problems the heuristic methods have played an important role, since they involve only values of functions in the process, regardless if there is unimodality or even continuity in their derivatives. Despite the great emphasis in the development of global optimization methods and their application to several different fields (DEDE et Al., 2019), researchers are even far from the attainment of a method that can be applied with the same efficiency to any class of problems (KRIPKA, 2004).

This work presents the application of Harmony Search method to the optimization of reinforced concrete building frames. To achieve this objective the cross sections dimensions, the area of steel and the concrete strength of beams and columns were taken as design variables. The constraints related to dimensions and strength were based on the Brazilian standard ABNT NBR 6118/2007. This work is a sequence of former studies of our research group regarding the optimization of grillages and columns sections by heuristics methods. E.g., Medeiros and Kripka (2013) optimized reinforced concrete building grillages, considering elastic supports. In 2015, Kripka, Medeiros and Lemonge expanded this work to include automated grouping of beams, and in 2019 Boscardin, Yepes and Kripka implemented cardinality constraints to plane frames. Bordignon and Kripka (2012) and Medeiros e Kripka (2014) implemented the cost minimization of reinforced concrete columns section by different optimization methods (Simulated Annealing and Harmony Search, respectively).

The next sections of this paper present a brief description of the optimization method, the developed formulation, some examples and the main conclusions.

2. HARMONY SEARCH OPTIMIZATION ALGORITHM

Harmony Search Algorithm (HS) is a metaheuristic proposed by Geem, Kim and Loganathan in 2001. It consists in an analogy to musical improvisation of jazz, where musicians try to find, through repeated attempts, the perfect harmony (best solution to a problem). Iterations are called improvisations or practice. Variables correspond to musical instruments. Values for variables are the sounds of instruments. Each solution is called harmony, and the calculation of the objective function is called aesthetic estimation. The method can be summarized in five steps:

– Initialization of problem and algorithm parameters: definition of the objective function, the constraints and parameters of the algorithm. Main parameters are Harmony Memory Size (HMS), Harmony Memory Considering Rate (HMCR), Pitch Adjusting Rate (PAR) and Maximum Improvisation (MI).

– Initialization of Harmony Memory: definition of first Harmony Memory (initial group of solutions). Harmony Memory (HM) is represented by a matrix, each line corresponding to a solution vector. The matrix has a number of rows equal to HMS and number of columns equal to the number of variables of the problem (N). Harmonies are generated randomly between a lower and upper range.

– Improvisation of a new harmony: from the initial solution, a new harmony is generated. This step is performed by using the parameters PAR and HMCR. For each variable of the new solution, a random number between 0 and 1 is generated. This number is compared to the value of HMCR (Harmony Memory Considering Rate). If the random number is lesser (probability equal to HMCR), the value of the respective variable in the new solution vector is retrieved from Harmony Memory existing. If the random number is greater (probability equal to 1-HMCR), a new value for the variable is generated. The choice of this new value can be done in two different ways. Again, a random number between 0 and 1 is generated and compared to the parameter PAR. If the number is less than the rate (probability equal to PAR), Harmony Memory is considered, but with little adjustment, defined by *bw* (maximum variation of tone) and a random number. If this is greater than PAR (probability equal to 1-PAR), the new value for the variable is randomly generated within the interval of possible solutions.

– Update of Harmony Memory: At each new harmony improvised, it is checked whether this is better than the worst harmony of Harmony Memory (HM), relative the objective function. If confirmed this condition, the new harmony replaces the worst harmony of HM.

– Check the stopping criterion: usually, the maximum number of improvisations MI. If it is not achieved, the algorithm returns to the third step (improvisation of a new harmony).

Regarding the original work of Geem, Kim and Loganathan, several improvements and variations of the method have been proposed by other authors. An extensive study regarding these variations can be found, e.g., in Ingram and Zhang (2009), and in Fourie, Green and Geem (2013).

Mahadavi, Fesanghary and Damangir (2007), for example, refined the method by developing the Improved Harmony Search Algorithm (IHS). It was suggested in IHS the dynamic variation of parameters PAR and *bw*, according to the number of iterations, between minimum and maximum limits for each factor. PAR increases linearly, while the parameter *bw* decreases exponentially.

Along with the inclusion of the variable parameters of IHS, other variations in original algorithm were proposed by Medeiros and Kripka (2017), and incorporated into present work:

-Instead of generating all initial solutions randomly, as usual, one predefined solution can be included in the Harmony Memory;

-To avoid premature convergence to local minimum, the Harmony Memory is restarted when all solutions achieve similar values. Only the best current solution is included in this new HM;

-As an additional stopping criterion to avoid unnecessary calculations, the algorithm developed in this work can terminate the search when the best solution found does not varies after successive NR restarts.

3. PROBLEM FORMULATION

Considering rectangular cross sections of beams and columns, the objective is to minimize the total cost of the elements of a plane frame. The cost function considers the total cost of materials, being: cost of concrete per unit volume, cost of the reinforcement per unit mass and cost of formwork per unit area. All costs provide a relative value per unit length of the optimized element. This cost is multiplied by the total length of beams and columns, giving the total cost of the frame obtaining a configuration that is capable of producing internal forces (N_{rd} and M_{rd} to columns and M_{rd} and V_{rd} to beams) equal or higher than the applied external loadings (N_{sd}, M_{sd}, V_{sd}), with minimal cost. The verification is made according to Brazilian standard ABNT NBR-6118/07, regarding strength, slenderness and limitations of size, spacing, and steel ratio.

Regarding columns, the design variables are the values that represent the cross sectional dimensions and the steel bar diameters. To beams, the width is fixed, since its influence is not significant in relation to the height. In addition, the reinforcement section can be easily obtained from the height. Based on this fact, just the height of concrete section and the concrete strength were considered as design variables to beams. In this study, the dimensions of the cross section of beams and columns were considered varying in steps of five centimeters. The diameters of the reinforcement bars of columns were limited to those available in commercial stores and the beams steel areas were considered as continuous. In sum, a total of eight discrete design variables were considered to a given configuration. A more precise description of the formulation of beams and columns optimization can be found, respectively, in Medeiros and Kripka (2013), and in Bordignon and Kripka (2012). In Bordignon and Kripka (2012), a column section was optimized, given external loads N_{sd} and M_{sd}. In the present work, this formulation was adapted in order to consider the additional stresses due to the slenderness of the column, with the internal forces obtained directly from the analysis of the whole frame.

The formulation was implemented using the Fortran programming language, by the association of Harmony Search optimization method and frame analysis by the displacement method.

The input parameters used by the optimization software are: number of nodes, number of beams, number of columns, nodal coordinates, position of each element, cross sectional dimensions, support conditions, imposed loads, characteristic strength of steel, characteristic strength of concrete, unit cost of concrete, unit cost of steel and unit cost of formwork. For the simulations, several initial solutions were utilized, resulting in the convergence to a single optimal solution, regardless the cross-sectional dimensions initially adopted to beams and columns.

4. RESULTS

This section presents some results obtained from the application of the implemented formulation. The aim of these numerical simulations was to show the efficiency of the formulation, as well as to identify the influence of factors such as resistance class, material costs and beams/columns costs on the optimal design of reinforced concrete building frames. The examples were adapted from Kripka et al (2015) and from Guerra and Kiousis (2006).

To all examples, the following common values were considered to costs, in Brazilian currency (R$): CA-50 steel bars = 10.04 R$/kg; formworks = 59.00R$/m^2, and concrete = R$ 320.00 R$/m3 (strength of 20MPa), R$ 333.47 R$/m^3 (25MPa), R$ 344.70 R$/m^3 (30MPa), R$ 357.05 R$/m^3 (35MPa), R$ 370.52 R$/m^3 (40MPa), R$ 416.56 (45MPa) and R$ 494.03 to strength of 50MPa. In addition, a dead load of 23 kN/m and a live load of 7 kN/m were applied to all beams.

Regarding Harmony Search, the following parameters were considered: HMS = 50, $HMCR$ = 0.90, $PAR_{MÁX.}$ = 0.50, $PAR_{MÍN.}$ = 0.30, $BW_{MÍN.}$ = 1, $BW_{MÁX.}$ = 2 and $NI_{LIM.}$ = 500,000.

4.1 Example 1

The first structure analyzed, illustrated in Fig.1, consists in a frame composed by a single beam with length L, and height of 3m. A 25MPa concrete strength was considered.

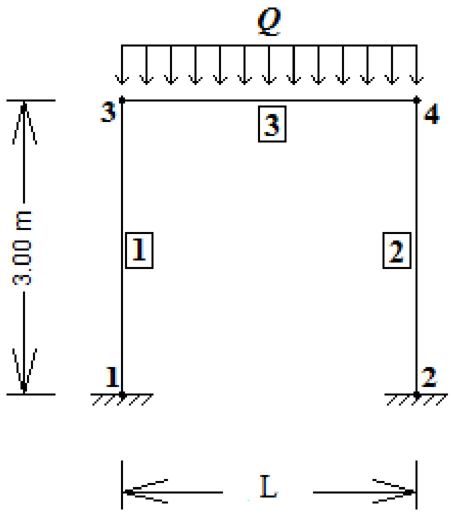

Fig. 1 Structure of example 1

Figure 2 presents the minimum total cost obtained to the example, optimized to length L varying from 1 to 20m. The relative cost of beams and columns is illustrated in Figure 3. It can be seen that, in exeption to small spans, most part of total cost is due to beams cost.

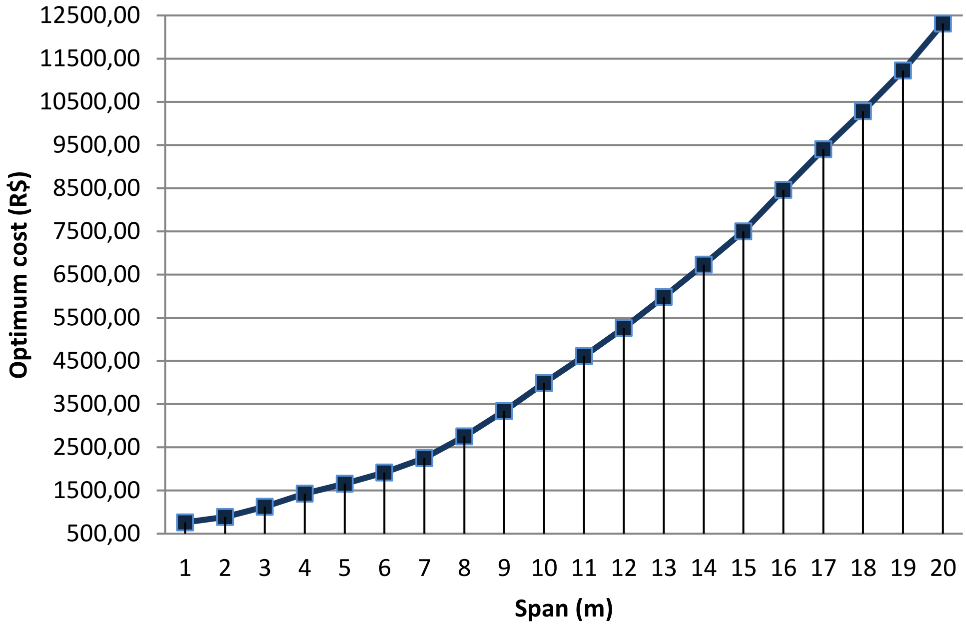

Fig. 2 Minimum total cos to example 1

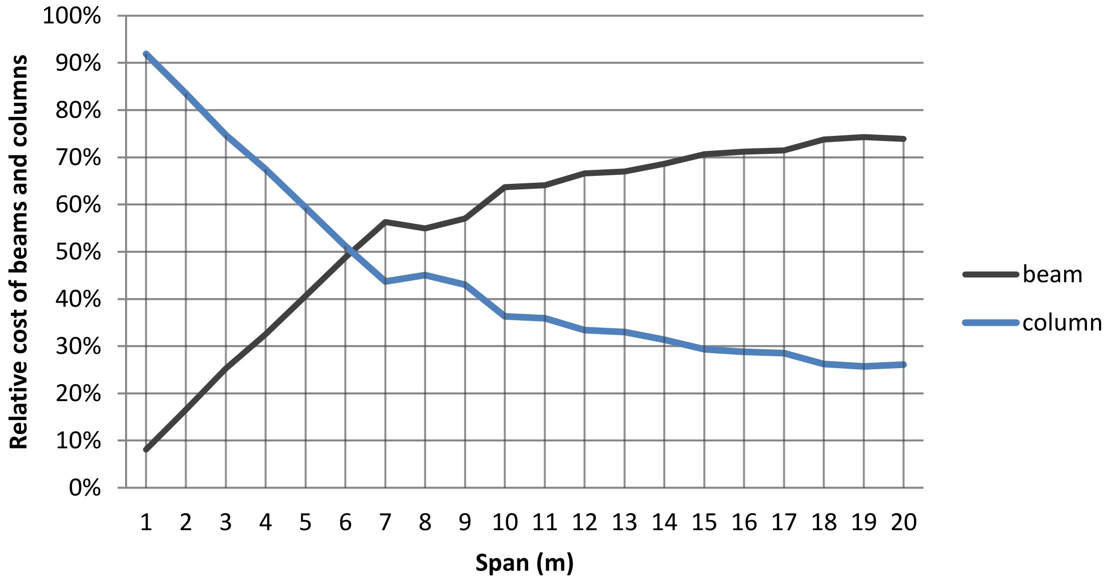

Fig. 3 Relative cost of beams and columns to example 1

The relation of the cost of each material to total cost can be seen in Figure 4. It can be observed that, in general, the cost of steel corresponded to the major part of total cost, followed by formworks.

To the columns, the steel ratio ranged from 0.98% to 2%. To beam, this relation varied between 0.58% and 1.13%.

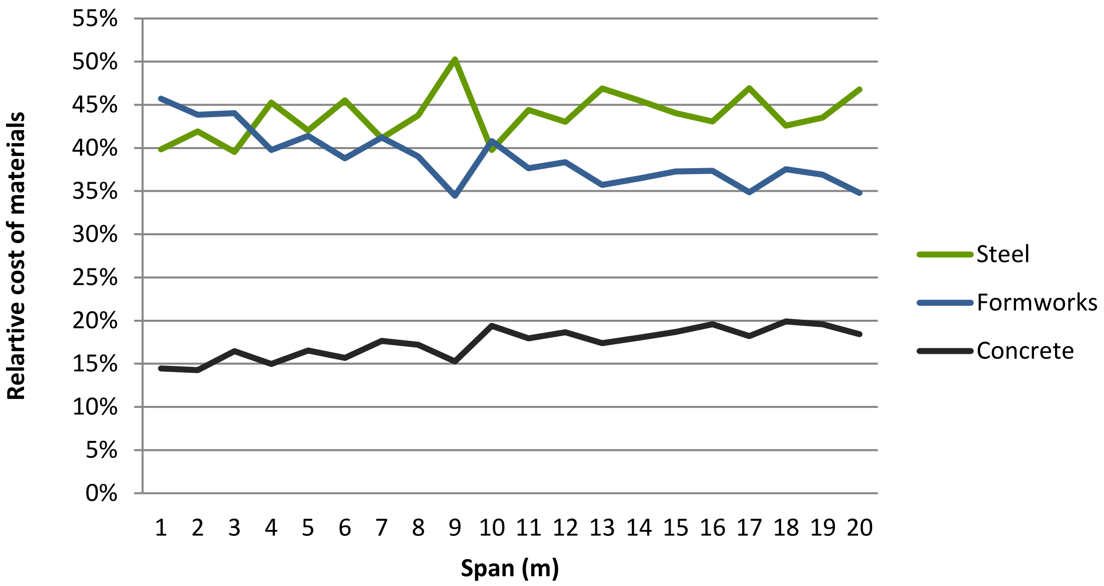

Fig. 4 Relative cost of materials to example 1

4.2 Example 2

The structure of example 2 consists in a 20m frame, composed by a variable number of equally spaced columns. The analysis started by considering 11 columns (spans of 2 m), according to Figure 5, up to 2 columns (configuration equal to Structure 1). Beams and columns width were set at 0.2 m, with columns height of 3 m.

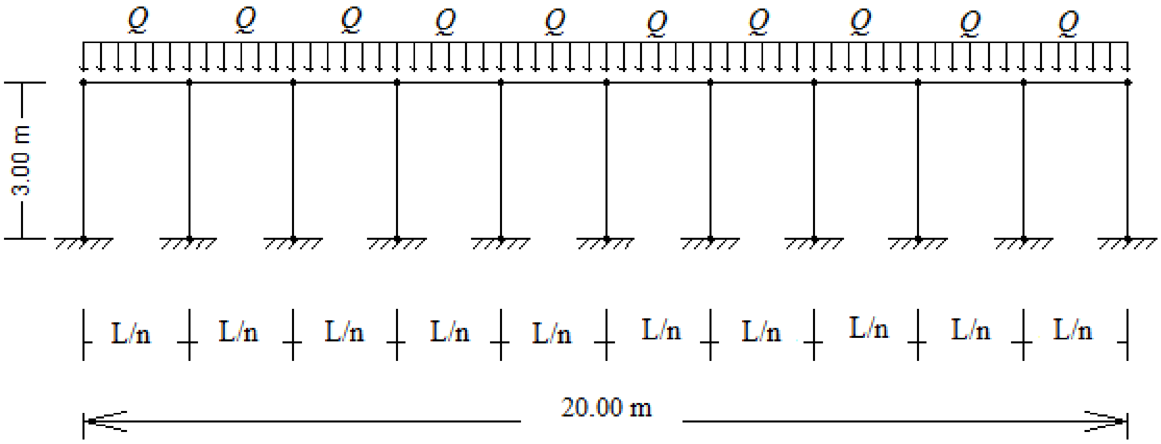

Fig. 5 Initial configuration of example 2

The beams height/span corresponding to optimal cost ranged from 7% to 13%, as illustrated in Figure 6. This is in accordance with the average value of 10%, a practical relation usually adopted to pre-size reinforced concrete beams and obtained by Medeiros and Kripka (2013) to isolated beams.

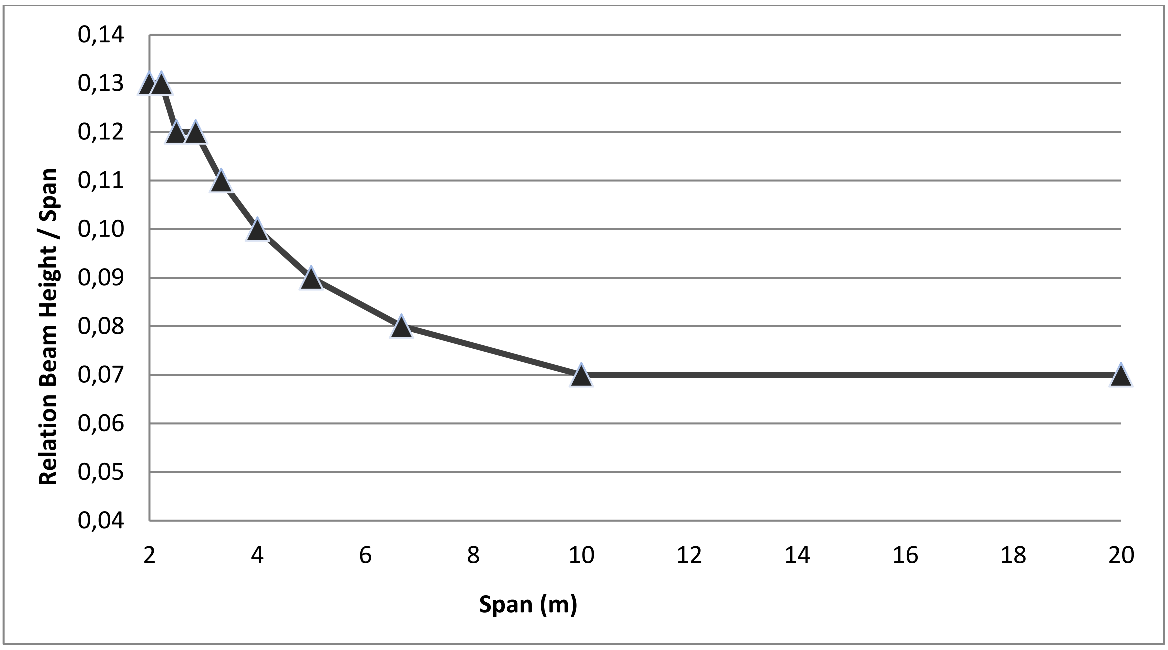

Fig. 6 Example 2: relation height/span of beams

The total cost of the frame was computed while the number of columns was gradually reduced. Figure 7 illustrates that, to the example, the span which corresponded to minimum cost was about 3,3 m. The worst situations corresponded to the largest spans.

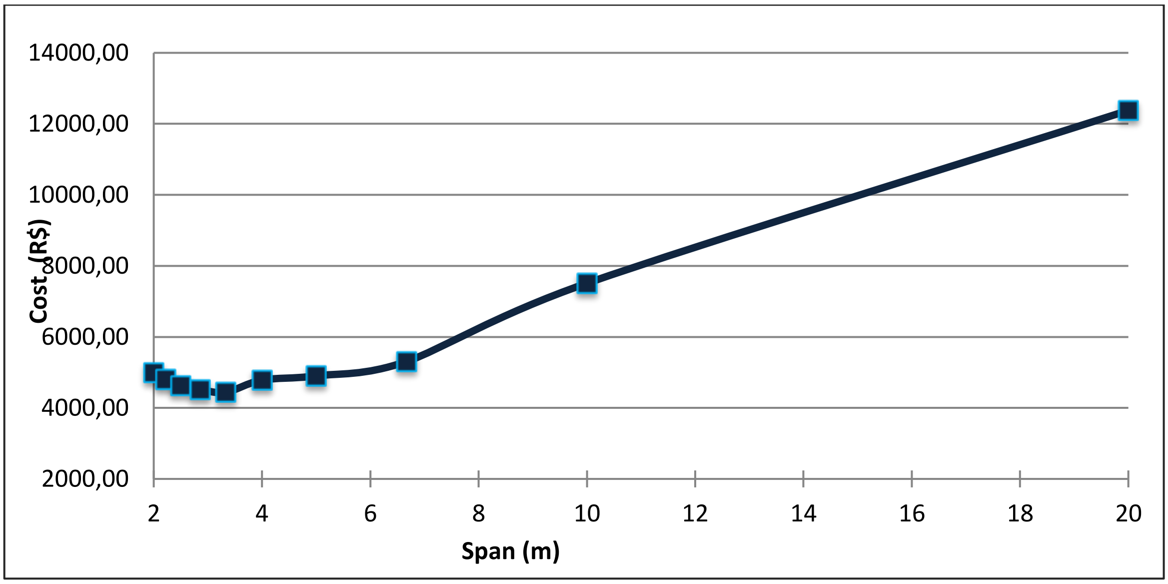

Fig. 7 total cost of the frame of example 2

4.3 Example 3

The structure of this example is composed by five floors, as illustrated in Figure 8. In order to study the influence of concrete strength on the total cost, five different strenghts were considered, ranging from 20MPa to 50MPa.

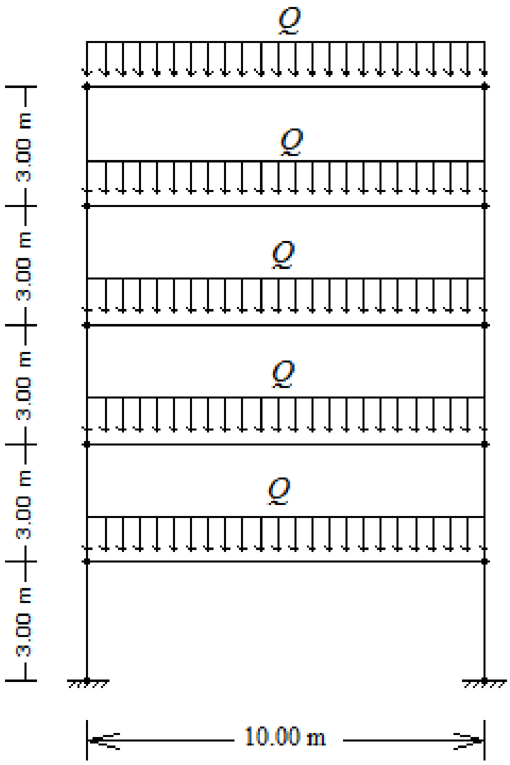

Fig. 8 Structure of example 3

The optimum cost obtained to each considered strength is plotted in Figure 9. It can be seen that the lowest cost corresponded to an intermediate concrete resistance of 35 MPa, being 20 MPa the highest cost.

According to previous studies of Medeiros and Kripka (2013), when just the beams are optimized, the lowest cost corresponds to small concrete strengths. In opposition, when only columns are considered, the lowest cos tis obtained to highest strengths (BORDIGNON and KRIPKA, 2012). Based on these researches, the obtainment of an intermediate strength to the whole frame represents a coherent result.

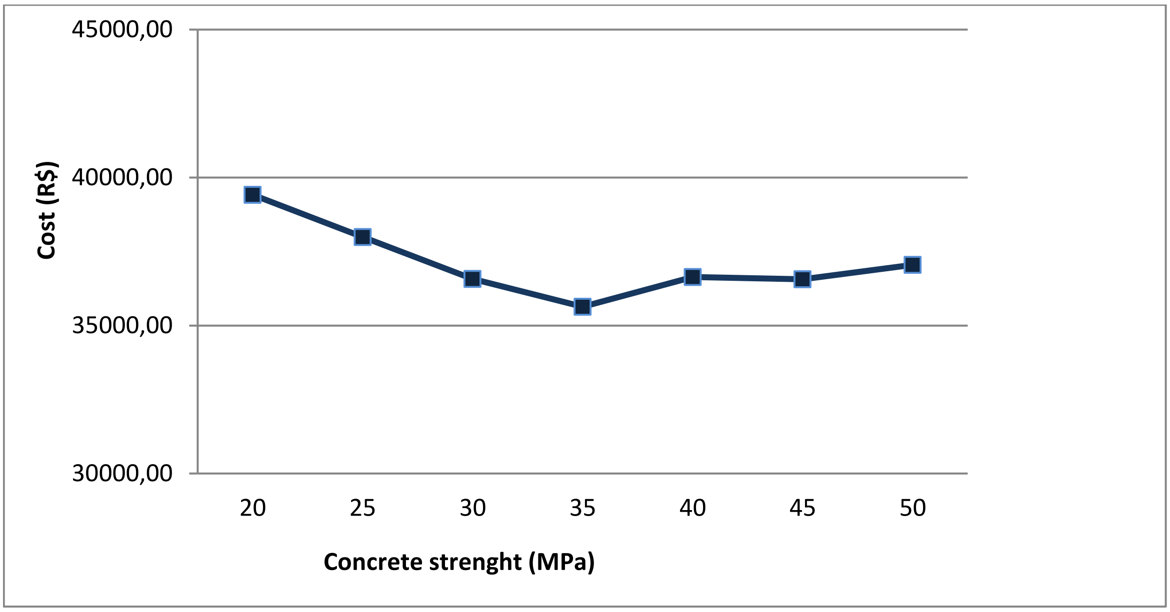

Fig. 9 Cost versus concrete strength to example 3

5. CONCLUSIONS

This work dealt with the optimization of reinforced concrete building frames, following the requirements of the Brazilian standard NBR 6118 (ABNT 2007), and using the Harmony Search optimization method. To the examples analyzed, the optimization method was quite efficient in minimizing structural cost. The structures optimized allowed the obtainment of some parameters such as economic steel ratio, concrete strengths and, height/span relation. Although structures with higher complexity need to be studied in order to generalize the obtained results, such parameters can aid structural designers to reduce the global cost of building structures.

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