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Optimization of Reinforced Concrete Frames by Harmony Search Method

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Abstract

The aim of this work is to present a procedure developed in order to minimize the cost 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). The total cost, composed by the costs of concrete, steel and formworks, was minimized by the usage of Harmony Search Algorithm (HS), an optimization method developed by Geem, Kim and Loganathan (2001), inspired by the observation that the aim of music is to search for a perfect state of harmony. The search process is compared to a musician's improvisation process. Some structures were analyzed, and the results were compared to those obtained from the conventional design procedure, in an attempt 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. This work is a sequence of former studies of the authors regarding optimization of grillages and columns sections by heuristics methods.

Keywords: Building. Frames. Optimization. Reinforced Concrete. Harmony Search Method.

1. Introduction

Structural analysis and design usually involve both highly complex procedures and a great number of 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. Also, 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.

The great development of structural optimization took place in the early 60's, when 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, researchers are even far from the attainment of a method that can be applied with the same efficiency to any class of problems.

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 [1]. This work is a sequence of former studies of the authors regarding optimization of grillages and columns sections by heuristics methods (e.g. [2] and [3]).

The next sections of this paper present a brief description of the optimization method, the developed formulation, simple application example and some preliminary conclusions.

2. Harmony Search Optimization Algorithm

Harmony Search Algorithm (HS) is a metaheuristic proposed by Geem, Kim and Loganathan in 2001 [4]. 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 [5], and in Fourie, Green and Geem [6].

Mahadavi, Fesanghary and Damangir [7], 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 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 a plane frame, the objective of optimum design is to obtain 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 [1], regarding strength and limitations of size, spacing, and steel ratio.

Regarding columns, the design variables are the values that represent the cross section dimensions and the steel bar diameters, as well as the concrete strength. 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 as discrete, 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. The concrete strength can vary in steps of 5MPa.

The cost function to be minimized in the optimization process 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.

4. Preliminary Results

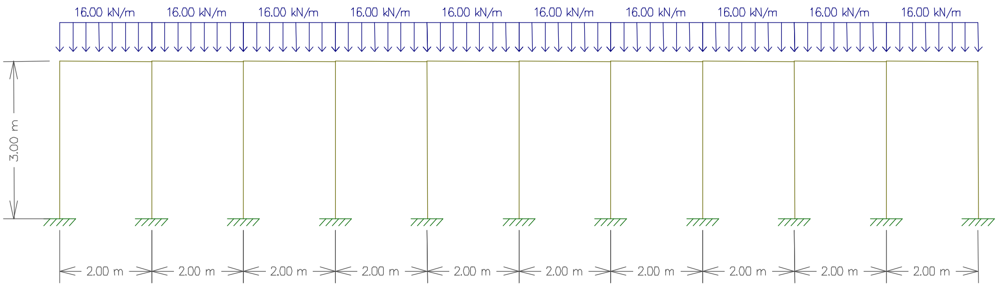
The formulation was implemented using the Fortran programming language, by the association of Harmony Search optimization method and frame analysis by the displacement method.

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.

Some numerical simulations were performed in order to test the efficiency of the proposed procedure. For these simulations, several initial solutions were utilized, resulting in the convergence to a single optimal solution, regardless the cross sectional initially adopted to beams and columns.

Some preliminary results are presented in the sequence of this work. The example consists in a 20 meters frame, composed by a variable number of columns. The analysis started by considering 11 columns (spans of 2 m), according to Figure 1. Beams and columns width were set at 0.2 m, with columns height of 3 m. A load of 16 kN/m was applied to beams, with the self weight computed automatically, based on the specific weight of the material (25 KN/m^3). The characteristic concrete strength (*fck*) was equivalent to 25 MPa, with the following unit costs, denominated in Brazilian currency (R$): CA-50 steel bars = R$ 3.97/kg; CA-50 steel bars = R$ 3.89/kg; formworks = R$ 8.68/m^2, and concrete = R$ 233.55/m^3.

Figure 1: example - original frame



To the original configuration, the optimized sizes of concrete section and the amount of gauges of the elements were achieved, and the corresponding total cost was computed. After each analysis, the number of columns was gradually reduced, in order to identify the optimal spacing. Figure 2 illustrates the results obtained, indicating that the optimal span was about 4 m to the example. It can be stressed that this result is quite similar to those suggested by practitioners. In this case, the optimal span corresponds to a relation beam height / span of 13.33.

Figure 2: example - cost versus span to variable number of columns

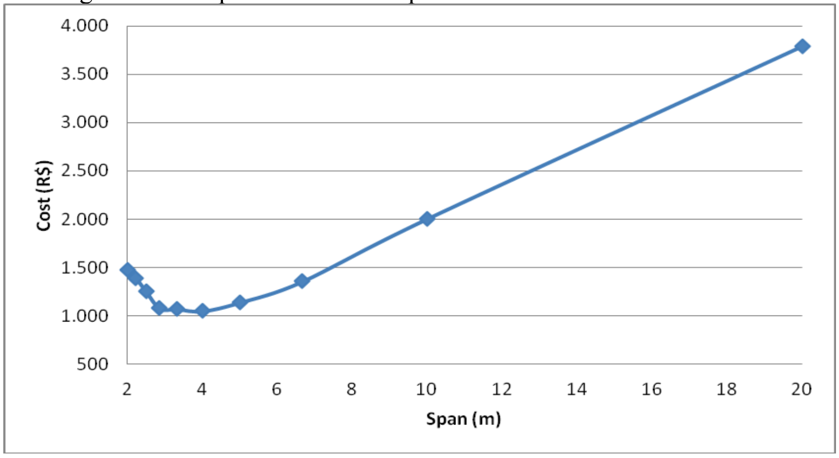


Figure 3 presents the relative cost of elements (beams and columns). It can be seen that the beams correspond to the major part of total cost to spans greather than 5 m. In addition, based in Figure 4 it can be observed that, despite the span considered, the main cost is due to the amount of steel, followed by concrete.

Figure 3: example – relative cost of elements

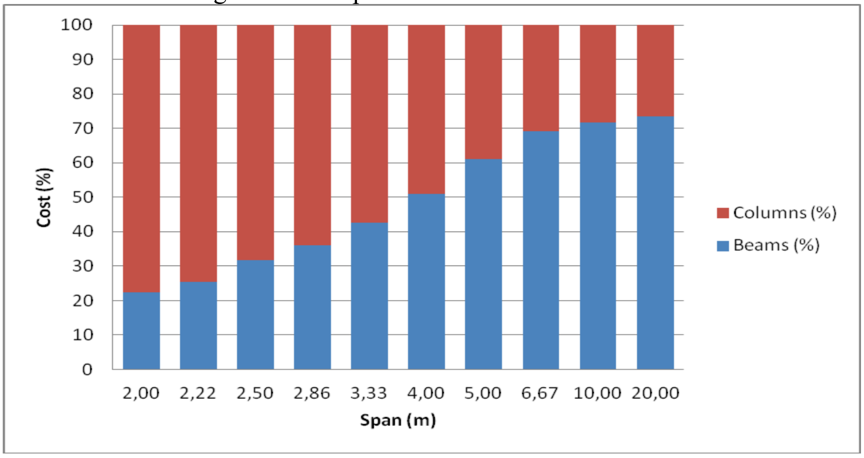
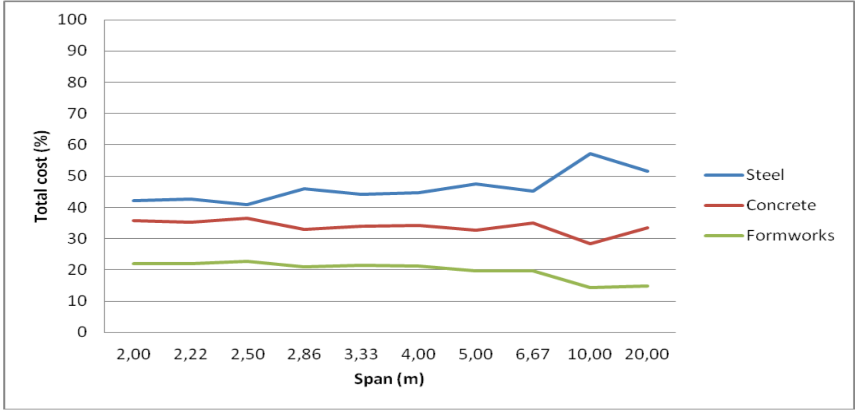


Figure 4: example – relative cost of materials



In order to assess the behavior of Harmony Search when compared to other heuristics, the optimization of isolated elements was performed with both Harmony Search and Simulated Annealing. Both methods led to similar results, but the number of function evaluations was much larger with Simulated Annealing. In addition, it was observed that optimal cost decreases rapidly to HS, when compared to SA.

5. Conclusions

This work dealt with the problem of 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 software has been an important tool for pre-sizing of reinforced concrete elements. To the example presented in this work, the optimal span was about 4 m, coincident with the practice. As observed in former studies developed by the authors, the steel accounts for the biggest part of the overall cost of elements, followed by concrete and formworks.

Other structures with higher complexity are being studied in order to generalize the obtained results, as well as to obtain parameters to allow the designers to reduce the global cost of building structures.

6. Acknowledgements

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7. References

[1] Brazilian Association of Technical Standards, Procedures for the design of reinforced concrete structures. NBR 6118, Rio de Janeiro. (in Portuguese), 2007.

[2] R. Bordignon, M. Kripka, *Optimum Design of Reinforced Concrete Columns Subjected to Uniaxial Flexural Compression*, Computers and Concrete, 9(5), 345-358, 2012.

[3] G.F. Medeiros, M. Kripka*, Structural optimization and proposition of pre-sizing parameters for beams in reinforced concrete buildings*. Computers and Concrete, v. 11, p. 253-270, 2013.

[4] Z.W. Geem, J.H. Kim, G.V.A. Loganathan, *A New Heuristic Optimization Algorithm: Harmony Search*, Simulation, 76(2), 60-68, 2001.

[5] G. Ingram, T. Zhang, *Overview of Applications and Developments in the Harmony Search Algorithm. From: Geem Z.W. "Music-Inspired Harmony Search Algorithm"*, Springer, SCI191, pp. 15-37, 2009.

[6] J. Fourie, R. Green; Z.W. Geem, *Generalised Adaptive Harmony Search: A Comparative Analysis of Modern Harmony Search*, Journal of Applied Mathematics, Article ID 380985, 2013.

[7] M. Mahadavi, M. Fesanghary, E. Damagir, *An Improved Harmony Search Algorithm for Solving Optimization Problems*, Applied Mathematics and Computation, vol. 188, n. 2, pp. 1567-1579, 2007.