MULTIOBJECTIVE OPTIMIZATION OF REINFORCED CONCRETE BUILDINGS

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Abstract. The application of parametric and topological optimization in the conception of buildings is a problem of high complexity due mainly to the large number of variables of interest to be optimized and to its nature intrinsically multiobjective. Due to the computational development occurred in the last decades, it has arisen the opportunity for a broader study and development of numeric models in this field. For the conception of structural projects, it counts on vary computational programs that automate great part of the structural projects' conception process. However, in the stage of definition of the structural elements position, such as columns and beams, there is still a high level of dependency of the designer because it is long the time spent in the project's conception and not always the solution found is the most viable in economic and executive terms. In view of this problem, the current work aims to initiate the development of a computational model of structural optimization of buildings in reinforced concrete to decrease the designer dependency with the objective of minimizing the costs – such as concrete volume and steel weight – through the search of columns positions and its dimensions, restricted to an imposed architecture. It must be employed the evolutionary computation philosophy through the use of the heuristic method of genetic algorithms, in the generation of the various feasible solutions, which are obtained by the results of the model of analysis by spatial framed structures, based on the finite element method. For the generation of the cost function, it will be considered the determination of the section area of the column and the steel needed that attends the equilibrium of each reinforced concrete section subjected to biaxial (oblique) bending with axial force state. Lastly, it will be performed comparative studies, qualitative and quantitative, between structural conceptions with and without the optimization technique in order to verify the consequences of its use.

Keywords: Parametric Optimization; Reinforced Concrete Building; Genetic Algorithms; Position of Columns.

1 Introduction

Great advances occurred in the last decades in the design field with the development of some specific software for development of structural designs. There are several computational programs that can automate most of the structural conception process because they assist the designers in the development of complex structures and provide preliminary information, such as loads on foundation, structural members dimensions, structural detailing, and costs. However, at the stage of defining the distribution of structural elements there is still a high-level dependency on the designer. Usually, time spent on the structural topology conception, such as columns, beams and slabs, is long. This definition is based on the knowledge and experience of designer and, sometimes, the proposed solution is not properly feasible in economic and executive terms. Regarding these particularities, the advances in research about structural optimization are important because they intend to reduce time consumption on the design conception and minimize execution costs.

According to Oliveira [1] and Machairas, Tsangrassoulis and Axarli [2], the discussion about this topic is quite recent but not deeply explored and reproduced in a realistic approach as result of the great complexity in finding the Pareto optimality against the multiobjective and multi constraints that concern a building design. The reason of the scientific exploration of this topic is clear and this work intends to be the seed of a future construction and an artificial intelligence model seeking the automated structural conception, that is still dependent on the manual work of engineers in the design of buildings.

From this perspective, the current work aims to initiate the development of a computational model of structural optimization for buildings made of reinforced concrete that seeks to reduce the designer dependency and minimize the costs – such as its concrete volume and steel weight – upon the search of columns location and dimensions restricted to an imposed architecture by the use of the heuristic method of Genetic Algorithms (GA), in the generation of diverse feasible solutions which are obtained by frame bars analysis model based on the Finite Element Method (FEM). The structural optimization will have the minimization of an objective function that must attend the lowest total cost of material, in this article, it is taken into account only the dimensioning of the section and the steel weight of columns in reinforced concrete under oblique bending and axial load following the characteristic ratio of the parabola-rectangle diagram for compression and the tensile stress curve for steel, as referenced in NBR 6118 [3] through the Newton method for non-linear problems for equilibrium of the cross-section.

2 Optimization process

By following this methodology, the model proposal is based on application of the GA technique, so that it is developed an automatic generation model of the possible sets of columns and beams of the building, representing an initial population that implies in distribution of columns and beams of a referenced architectural plan, according to the procedure later explained in this article. Thus, the building model is automatically generated by the FEM with columns and beams, vertical loads, which represents permanent loads. It is defined an objective function - which must be minimized - it returns the steel amount, the cross-section area defined for each structural element following standard guidelines established by NBR 6118 [3]. Therefore, the processes that must be developed to generate the optimized model with the best disposal of columns and seeking the economic aspect as ideal solution.

2.1 Reference mesh

A process is developed for generation of a rectangular reference mesh with n horizontal divisions and m vertical divisions. Those should be associated to cartesian coordinates, which are equidistant and the possible positions to allocate columns. Automatically, the incidence of horizontal and vertical beams is obtained in this mesh.

Still in this computational routine beam locations are determined, which are distributed in every column set, connecting them in both directions of the design (horizontal and vertical). One example of the column and beam set elaborated by the routine is shown in Figure 1, with $n = 10$ and $m = 8$.

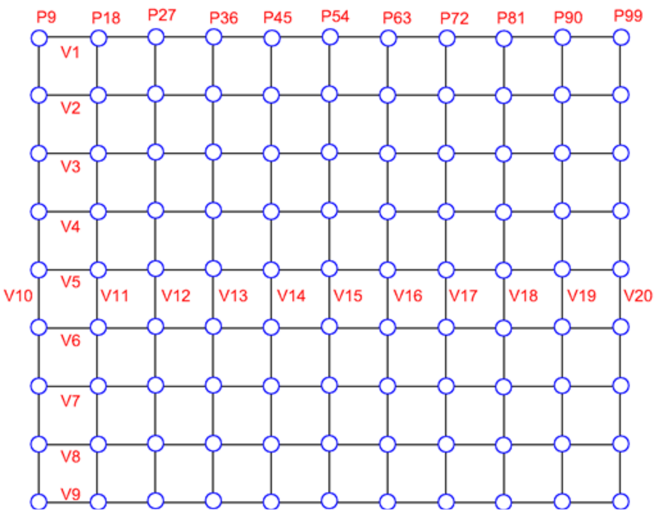

Figure 1 – Reference mesh of points defined by the routine.

2.2 Generation of column set

Using the network of points defined by the process described in section 2.1, it is employed a program based on GA, with a component library developed by Wall [18], from Massachusetts Institute of Technology, for the C++ programming language, called Galib, which is connected with the FEM model, written in Fortran language, via dynamic link library (*dll*). A function was developed to return a set of random integer numbers of length previously determined representing a number k of columns. Thus, it is removed from the reference mesh the $[(n+1)(m+1)-k]$ columns. For the beams, it was adopted the idea to maintain those that passes vertically and horizontally over the k columns and the corner beams. See in the Figures 2 and 3 a hypothetical example of selected points for columns: 2, 51, 80, 84. Another example is shown in Figures 4 and 5, in which the columns randomly selected from the reference mesh were 25, 48, 73, 91.

Distributed loads on floor are redistributed on the acting beams leading to the same resultant force, since that depending on the column position it could generate a different number of associated beams.

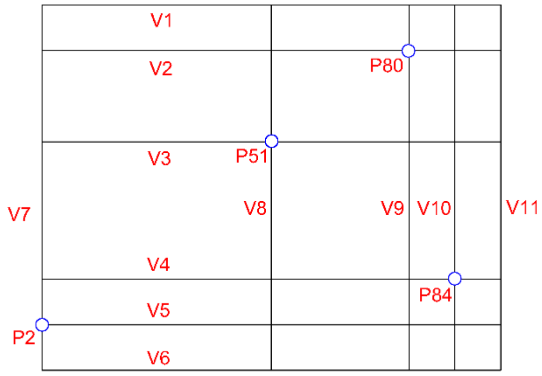

Figure 2 – Reference mesh with points 2, 51, 80 and 84 defined by GA.

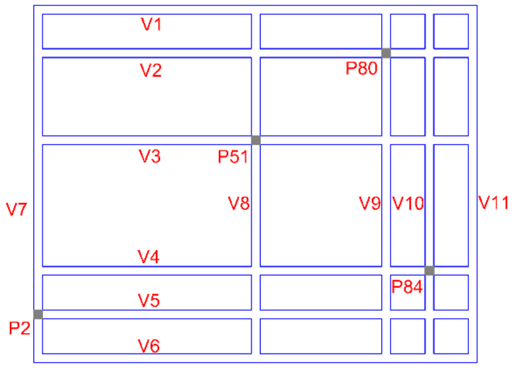

Figure 3 – Form's blueprint.

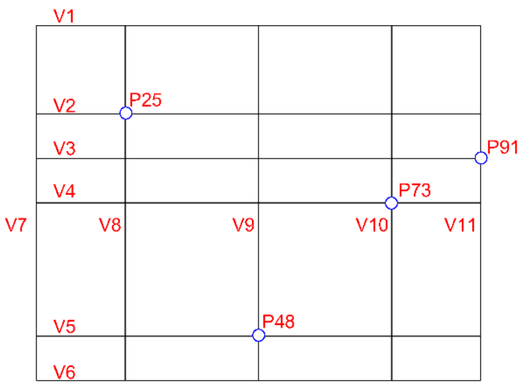

Figure 4 – Reference mesh with points 25, 48, 73 and 91 defined by GA.

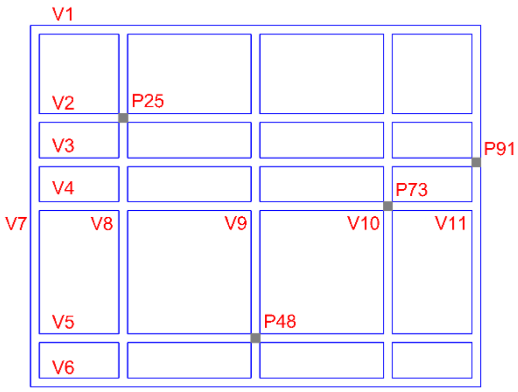

Figure 5 – Form's blueprint.

2.2 Building analysis

For the third process stage it was employed the building analysis model developed by Almeida [6] and extended by Aquino [7] that included foundations and geometric non-linear formulation, both based on FEM. Then, this model is automatically generated with k columns created by the GA, assembling a system with beams and columns, and, with addition of permanent and accidental loads (wind) for each floor. Thus, reactions, internal efforts and displacements are calculated for the entire structure, presenting alphanumeric results and drawing (dxf file).

2.3 Building designing

With the results provided from the FEM analysis of the building, it is performed the beams and columns sizing according to the standard guidelines [3]. The beam heights are calculated, its widths are determined as constant, while its steel area are calculated according to bending moments and shear internal efforts. The columns are dimensioned by the iterative searching for equilibrium of cross-section - applying the Newton-Raphson method - throughout the use of the resolution of the coupled equilibrium equations. It is considered nonlinearity for the concrete with the use of the characteristic diagram of the parabola-rectangle for compression and the idealized steel for tensile stress according to the standard guidelines [3].

Initially, a minimum value for dimension is considered for each column section. Due to standard guideline limits, it is not possible dimension the section for the oblique bending a certain column subject to the trio (N, M_y and M_z), such as the model automatically changes its geometry until it finds a dimension that enables the accommodation and its equilibrium. Thus, after the iterative balancing process, for each beam and column, the value of steel area and its cross-section is obtained, which can result the total weight of steel and total volume of concrete used in the parts, which can be added together, leading to the global calculation of steel and concrete volume:

$$Pt = Pv + Pp \tag{1}$$

$$Volt = Volv + Volp \tag{2}$$

where Pt, Pv, Pp, are respectively, the total steel weight of the beams and columns of the building, and $Volt$, $Volv$ and $Volp$, respectively, the total concrete volumes of the beams and columns in the building.

2.4 Final objective function

After the structural sizing, the objective function to be minimized (F) is obtained by the weighted sum of the total steel weight and volume of building as described in Equation (3).

$$F = Pt.p1 + Volt.p2 \tag{3}$$

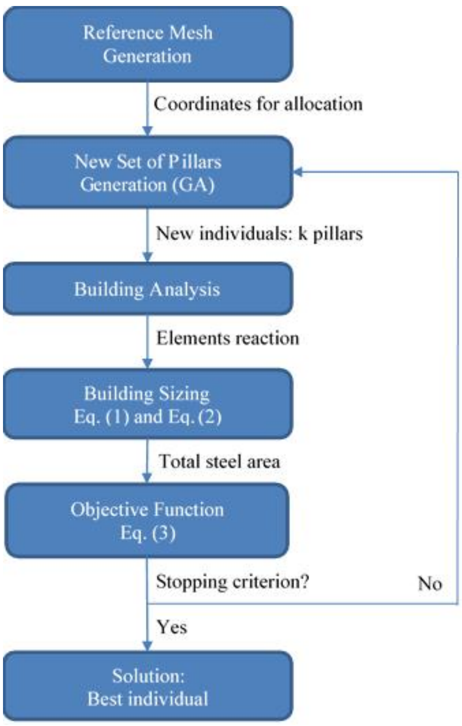

Figure 6 – Flow chart of the process to find the best columns positions.

where $p1$ and $p2$ are heuristically obtained weights to normalize the different values of the sum, since the sensitivity of Pt and $Volt$ are of different order of magnitude. Thus, in this optimization process, the result will be modified and analyzed repeatedly, according to the GA process that calls the building analysis model, and at the end, with the results of the concrete and steel quantities, for each group of columns and beams provided by the GA, a comparison of these results is carried out, so that it is possible to determine if a solution is the best compared to the others and select the group that best attends the design needs, reducing the consumption of concrete and steel. Figure 6 presents a simplified flowchart of the process to be used in the optimization process.

3 Numerical application

In the simulation of this example, the following information was used as input data for the model, a structure composed of 2 floors, ceiling height of 3 meters, with dimensions of $15x8$ meters, a network with values adopting $m = 15$, $n = 8$ e $k = 8$ columns, with a population of 50 and 200 genes, the reference grid model is shown in Figure 7.

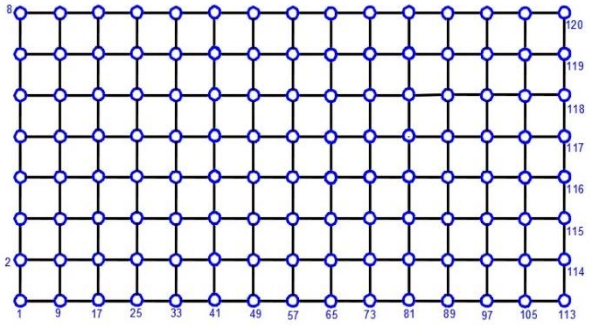

Figure 2 – Reference mesh.

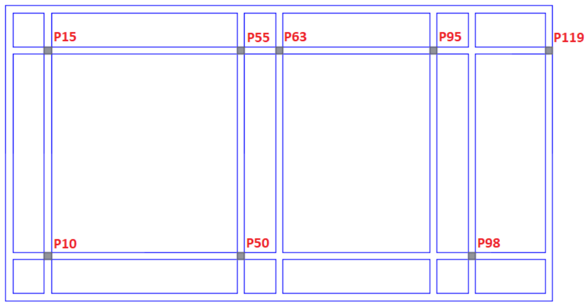

Figure 1 – Form's blueprint – Numerical application.

This simulation resulted in 8,632 cases, with time computing of 63,639 seconds, and the result demonstrated by the computational model presented the following set of columns and their coordinates: column 10 (2;2), column 15 (2;7), column 50 (7;2), column 55 (7;7), column 63 (8;7), column 95 (12;7), column 98 (13;2) and column 119 (15;7), disposal of these columns can be visualized in Figure 8. This architectural plan presented the following results: 1.92 m³ of concrete and 611.04 kg of steel. Using the reference of cost prices from SINAPI [8] for the composition of costs, the total cost is R$ 3,600.36 (presented in Table 1).

For comparison purposes with the numerical application presented in this section, a structural model was created with the same input data as the example, but with fixed column arrangement, following standards used by designers, such as column arrangement in corners and other columns being symmetrically distributed in the structure, avoiding long-span beams. The arrangement of the columns is shown in Figure 9, and it presents the following positions and coordinates: 1 (1;1), 5 (1;5), 8 (1;8), 57 (8;1), 64 (8;8), 113 (15;1), 117 (15;5) and 120 (15;8). The results obtained with this structural model were the following: 2.16 m³ of concrete, 874.81 kg of steel and total cost of R$ 5,009.64. Table 1 presents a comparison of sizing and final cost values obtained by the two models, conventional and automatically optimized.

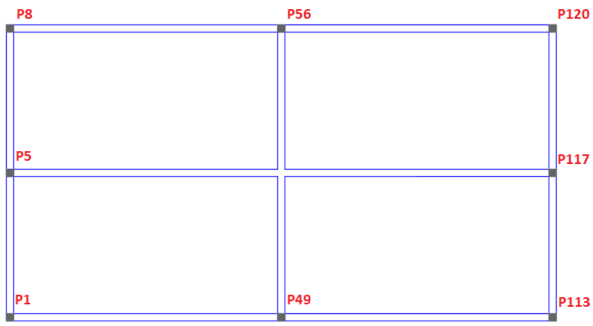

Figure 9 – Form's blueprint - Conventional design.

It can be inferred from Figure 10 the behavior of the structural optimization against the GA formulation, noting that the results found tend to decrease along time processing, thus improving its performance to find a result closer to the optimal one.

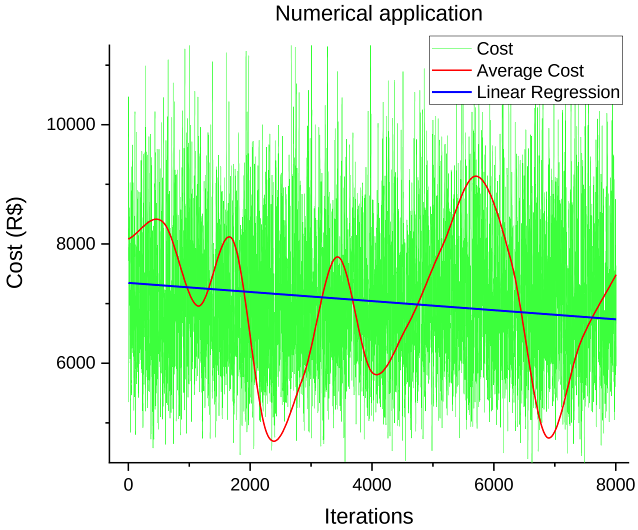

Figure 3 – Simulation results with GA.

Table 1 compares the results found in the conventional design (Figure 9) and results found through the simulation model for the example (Figure 8). In addition, this table presents the difference in obtained results. Cost composition and the quantitative of the main items that are significant for the cost of columns, concrete and steel. Besides, positional optimization reached a cost 28.13% lower than the conventional method.

Table 1 – Comparative results of traditional and optimized positioning

Conventional Design - Columns Arrangement						
Column			Steel Bars			Total Cost (R$)
Number	Bw x H (cm)	Concrete Volume (m³)	Quantify (unit)	ϕ Diameter (mm)	Weight (kg)	
1	20x20	0.24	4	20	58.81	365.83
5	20x20	0.24	4	25	91.89	530.24
8	20x20	0.24	4	25	91.89	530.24
49	20x20	0.24	6	20	88.22	511.97
56	20x30	0.36	8	25	183.78	1023.71
113	20x20	0.24	6	20	88.22	511.97
117	20x30	0.36	8	25	183.78	1023.71
120	20x20	0.24	6	20	88.22	511.97
	TOTAL	2.16			874.81	5009.64

Columns Arrangement - Optimized Positioning						
Column			Steel Bars			Total Cost (R$)
Number	Bw x H (cm)	Concrete Volume (m³)	Quantify (unit)	ϕ Diameter (mm)	Weight (kg)	
10	20x20	58.81	4	20	0.24	365.83
15	20x20	91.89	4	25	0.24	530.24
50	20x20	88.22	6	20	0.24	511.97
55	20x20	91.89	4	25	0.24	530.24
63	20x20	37.64	4	16	0.24	235.76
95	20x20	91.89	4	25	0.24	530.24
98	20x20	91.89	4	25	0.24	530.24
119	20x20	58.81	4	20	0.24	365.83
	TOTAL	611.04			1.92	3600.35

4 Conclusions

Among the contributions proposed by this work, there is an alternative to the positioning of the columns, aiming to reduce the dependence of the designers. Results of the traditional design method compared to results obtained through the present model developed, demonstrated the efficiency of this method and the importance of this research. If this analysis is done without the use of GA, for example, by using k = 4, n = 10 and m = 8, as exemplified throughout the article, there is a total of 3,764,376 possibilities. For each iteration analysis, it takes about 5 seconds, which would take approximately 217 days to perform all combinations. The use of GA optimization reduces the time cost of analysis, since its searching is more efficient, avoiding the need to compute all possible cases of each design.

Design limitations such as the maximum distances between columns, minimum and maximum span of beams, delimitation of the positioning of the columns avoiding positioning on door and window spans, obstruction of parking spaces, limitations of overhangs, etc., are some of the restrictions to be implemented into the model in the future. In the present study, the volume and reinforcement calculations of the beams were not considered, and this insertion is also an object for future work.

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