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Use of optimization for automatic grouping of beam cross-section dimensions in reinforced concrete building structures

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ABSTRACT

In the development of structural designs, in general, designers avoid varying the size of structural elements, seeking to group them as much as possible. These groupings produce aesthetic effects and facilitate formwork design for reinforced concrete frames, checks, and implementation. Therefore, the elements are pre-grouped into a smaller number of different cross-sections to provide an interesting and practical solution. However, the outcome is highly dependent on this grouping because the dimension of each element and, consequently, the overall cost, will be determined by the element that is the most stressed in each group. This paper minimizes the costs of the beams in reinforced concrete buildings using a grid model. The sizing is performed according to the Brazilian NBR 6118 standard [1], taking into account the flexural, shearing, torsional, and web reinforcements, in addition to checks on the service limit states (deflection and maximum crack opening). In addition to determining the beam height that leads to the lowest global cost, an automatic determination of the optimized group is performed, taking into account the required maximum number of groups. Several numerical analyses were performed using the computational implementation of the developed formulation. This paper presents the results obtained from an analysis of two floors. These results provide evidence that the chosen procedure may provide a significant reduction in the cost of a structure, even for a small number of different cross-sections. Thus, the determination of the optimum dimensions of the elements is less dependent on the designer's experience and sensitivity. The proposed procedure is easy to implement and may generate a significant reduction in the consumption of structural material when incorporated into the daily routine of project offices.

1. Introduction

The sizing of structural elements is an iterative process. The designer, based on his/her experience and intuition, determines the initial size of each element, which must satisfy the resistance and functionality requirements stipulated by current technical standards. Based on that, the design is further improved to reduce costs without compromising safety. Nevertheless, because there is a very large number of acceptable solutions to a given problem, it is unlikely that the best of all possible solutions will be found using this strategy. This is even more difficult with statically indeterminate structures, since a change in one element section will redistribute the efforts in the structure due to the alteration in relative stiffness of the elements. However, the use of a well-defined mathematical model to describe the problem may provide an optimal solution, based on a systematic process, in which the goals, constraints, and design variables are narrowed down. As regards to structural optimization, the smallest weight and lowest cost are the major goals to be achieved, and some constraints exist concerning the fulfillment of current technical standards.

A reduction in the costs for a reinforced concrete structure, if significant, may give construction companies and, especially, structural design offices, an advantage over their competitors. In addition, the rational use of the existing natural resources, provided by optimization, should also be taken into consideration.

Despite their potential application, optimization techniques have only been adopted to a limited degree by design offices. To expedite this process, it is crucial that the mathematical model considers the actual situations faced by designers, and that the result be applied without the need of adjustments that rely on a designer or that have some level of subjectivity.

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Several technical studies have addressed the optimal sizing of reinforced concrete structures, in which calculations are made using various classic optimization techniques. In most studies, the aim is to minimize concrete section costs while simultaneously meeting functional constraints based on design standards and satisfying constraints involving strength criteria. In those studies, the cross-sectional dimensions are often grouped to reduce the number of design variables, thereby lowering manufacturing costs. Nonetheless, the final outcome is highly dependent upon how this grouping is performed.

The aim of this paper is to apply an optimization technique to minimize the costs of beams in reinforced concrete buildings, while grouping structural elements automatically. For this goal to be met, a software program was devised by combining a structural analysis of the floor of a building using a grid model, the sizing of reinforced concrete beams, and a heuristic optimization method known as simulated annealing. The sizing of structural elements in terms of the ultimate and serviceability limit states was based on the Brazilian NBR 6118 technical standard [1], taking into account the flexural stress, shearing, torsional stress, and web reinforcements, in addition to checks on the maximum deflection and crack opening. The optimized grouping of elements was assessed by the so-called cardinality constraints (CC), after determining the maximum number of different cross-sections in the structure.

This paper is an extension of the authors' previous studies on the optimization of reinforced concrete building structures [3] and the use of cardinality constraints, both for steel frames [4] and reinforced concrete frames [16]. In [3], a formulation was developed and implemented to minimize the cost of building floors according to a grid model. This study aimed at identifying pre-sized beam parameters and the importance of the costs related to the forms, concrete, and steel in the optimized cost. The work developed in [4] highlighted the importance of considering the cardinality constraints in the optimization of steel gantries by achieving a significant reduction in the total weight of the structure. In [16], the previously developed formulation for the optimization of reinforced concrete structures was expanded by the incorporation of cardinality constraints. While in [16] the main objective was to introduce the proposed formulation and illustrate the optimization procedure, the present paper focuses on extending the results obtained and investigating how the maximum number of groups of elements influences the optimal costs. The authors are unaware of the existence of a similar study on reinforced concrete structures or the structural model chosen here.

The remainder of this paper is organized as follows. Section 2 briefly describes the basis of the structural optimization and the adopted optimization method (simulated annealing), as well as some applications to the optimization of reinforced concrete structures. Section 3 shows the proposition for the optimization problem. Section 4 gives some examples of the application of the proposed technique to a variable number of groups. Section 5 presents the conclusion.

2. Structural optimization

In structural engineering, optimization techniques have been constantly developed and applied to a wide array of problems in an attempt to find the best sets of material, topology, geometry, and/or cross-section dimensions for different structural systems [5].

The algorithms used for the solution of an optimization problem can be either deterministic or probabilistic. Deterministic optimization methods, also called classic methods, in which mathematical programming is included, are usually based on the calculations of first-order derivatives or second-order partial derivatives. Heuristic methods, based on probabilistic algorithms, introduce stochastic data and parameters in the optimization process, solving the problem from a probabilistic perspective.

Mathematical programming methods have some limitations, including difficulty in identifying global optimal solutions because they are dependent on the starting point, difficulty in working with discrete variables, and difficulty in performing non-differentiable functions. An essential characteristic for the application of classic methods is the need for the objective function to be continuous and differentiable in the search space. However, this does not occur in most practical engineering problems, thus hindering their application.

Heuristic methods do not use the calculation of derivatives. Instead, they directly search for solutions in the feasible space. However, these methods require a larger number of assessments of the objective function value, and are computationally more expensive than methods based on mathematical programming. Thus, they should not be used injudiciously, but only for problems for which mathematical programming is a limitation.

Heuristic methods include a large number of algorithms such as simulated annealing, genetic algorithms, ant and bee colony algorithms, harmony search, and particle swarm optimization. Despite this wide variety, genetic algorithms and simulated annealing are still the most popular methods and, therefore, have a larger number of applications [5,6].

Simulated annealing is a heuristic method based on statistical mechanics, which dates back to the annealing process, and was introduced by Kirkpatrick et al. [7]. In the physical process of solid hardening, a material is quickly heated and slowly cooled to eliminate its structural flaws. If the cooling is sufficiently slow, the final configuration of the material will correspond to the minimum energy state. On the other hand, quick cooling will result in a metal with a weak and brittle structure.

In brief, in simulated annealing, a single neighboring state s' of the current solution s is randomly generated in each iteration. The difference (Δ_f) between the quality of the new solution s' and the quality of the current solution s (Eq. (1)) is calculated to assess the acceptance of this new solution s'.

$$\Delta_f = f(s') - f(s) \tag{1}$$

In a minimization problem, if the value of Δ_f is less than zero, the new solution s' is automatically accepted and can be substituted for s. Otherwise, the acceptance of the new solution s' depends on the probability established by the Metropolis criterion, as shown in Eq. (2):

$$p = \exp\left(\frac{-\Delta_f}{T}\right) \tag{2}$$

As the temperature drops throughout the process, there is a higher probability of acceptance of new solutions in the initial stages. This probability decreases throughout the process, reaching a point (when the temperature is close to zero) at which only those movements that improve the cost function are accepted.

Several works published in the past few years successfully used simulated annealing for structural optimization.

Hasançebi and Erbatur [8] used this heuristic and optimized a 942-member truss tower, an 18-member truss, and a 47-member plane truss tower. In the latter two cases, the geometries of the models were optimized, along with their cross-sections. Discrete variables were used. A comparison of the results with those of other studies showed that the proposed simulated annealing algorithm outperformed genetic algorithms. Park and Ryu [9] proposed altering the parameters in order to improve the heuristics. They optimized the weights of two structures usually found in structural optimization problems: 10-member plane trusses and 25-member