MecSol 2017 – 6th International Symposium on Solid Mechanics
Joinville, SC - Brazil, April 26-28, 2016

INFLUENCE OF LIMIT STATES ON THE OPTIMIZATION OF REINFORCED CONCRETE BEAMS

Marcela A. Juliani[1]*, Wellison J. S. Gomes[1]

[1]Department of Civil Engineering, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

*Corresponding author: marcelajulianii@gmail.com

Abstract: Most current structural design codes are based on the concept of limit states, that is, when a structural element fails to meet one of its purposes, it is said that it has reached its limit state. According to the Brazilian code ABNT NBR 6118:2014, in the design of reinforced concrete structures, the following limit states must be checked: A. Ultimate Limit State (ULS), related to collapse or any other way of structural ruin that results in the discontinuation of the structure use; B. Serviceability Limit State (SLS), related to the structures durability, appearance and performance and comfort of the user. However, there are not many studies in the literature that point out the influence of such limit states on the optimal design of a structural element. In view of this, this paper presents an optimization scheme for reinforced concrete structures, based on the lowest cost, considering two groups of constraints: the first is related to the ULS and the second to the SLS. The optimal characteristics of a structural element subject to each group of constraints, individually, as well as to both groups simultaneously, are discussed. The methodology is applied to simply supported beams using genetic algorithms to solve the optimization problem, since this problem involves several local minima. The objective function employed corresponds to the cost of the structural element, which includes the consumption of concrete, steel and formwork. The limit states are formulated according to the recommendations of the ABNT NBR 6118:2014. As a result, predominant characteristics were observed in the optimal sections, according to the limit states: for ULS, the sections presented more steel reinforcement; in the SLS predominance of concrete occurred; in ULS+SLS the optimal factors remained within the limit formed by ULS and SLS.

Keywords: optimization, reinforced concrete, limits states, genetic algorithms.

Dear author,

In the stage of preparing your full work for evaluation, after receiving approval of the corresponding abstract, we kindly ask you to follow the next steps:

1. Update your approved abstract (you might want to introduce modifications) and submit it now in a written version according to the abstract template (many abstracts were introduced directly into the websystem). This version of the abstract will compose the abstracts booklet to be distributed to the participants when registering;

2. Fill the form in the next page, indicating to which section you would like your work to be directed. This will help organizing the sessions according to the mini-symposia advertised rather than in the areas and subareas present in the websystem. We apologize for this possible confusion. The reason is that we are using the websystem provided by ABCM, which does not allow us to introduce thematic sessions freely.

If any doubts arise, please contact us. Your presence in MecSol 2017 will help making this a very successful event. We look forward to seeing you in Joinville!

With kind regards,

The Organizing Committee
MecSol 2017

6 th International Symposium on Solid Mechanics

Select the box to select the Mini-Symposia:

[ ] Multiaxial and Fretting Fatigue (Edgar Mamiya and Lucival Malcher);

[ ] Composite Materials (Ricardo de Medeiros);

[ ] Constitutive Models I - Plasticity and Damage (Lucival Malcher, Miguel Vaz Jr. and Edgar Mamiya);

[ ] Constitutive Models II - Viscoelastic and Viscoplastic Solids: Models and Applications (Heraldo Mattos);

[ ] Impact Engineering (Marcílio Alves);

[ ] Structural Reliability Methods and Reliability-Based Design Optimization (André Beck);

[ ] Topology Optimization of Multifunctional Materials, Fluids and Structures (Eduardo Lenz Cardoso e Emilio Carlos Nelli Silva);

[ ] Topological Derivatives: Theory and Applications (André Novotny);

[ ] X-FEM, G-FEM and Meshfree Methods (Roberto Dalledone Machado and Rodrigo Rossi);

[ ] High Order Finite Elements (Marco Lúcio Bittencourt);

[ ] Nonlinear Analyses (Eduardo Campello);

[x] Other section;

MECSOL Joinville 2017

April 26-28, 2017
Joinville, Santa Catarina, Brazil

Influence of Limit States on the Optimization of Reinforced Concrete Beams

Marcela A. Juliani
Department of Civil Engineering
Federal University of Santa Catarina
marcelajulianii@gmail.com

Wellison J. S. Gomes
Department of Civil Engineering
Federal University of Santa Catarina
wellison.gomes@ufsc.br

ABSTRACT

Most current structural design codes are based on the concept of limit states, that is, when a structural element fails to meet one of its purposes, it is said that it has reached its limit state. According to the Brazilian code ABNT NBR 6118:2014 [1], in the design of reinforced concrete structures, the following limit states must be checked: A. Ultimate Limit State (ULS), related to collapse or any other way of structural ruin that results in the discontinuation of the structure use; B. Serviceability Limit State (SLS), related to the structures durability, appearance and performance and comfort of the user. However, there are not many studies in the literature that point out the influence of such limit states on the optimal design of a structural element. In view of this, this paper presents an optimization scheme for reinforced concrete structures, based on the lowest cost, considering two groups of constraints: the first is related to the ULS and the second to the SLS. The optimal characteristics of a structural element subject to each group of constraints, individually, as well as to both groups simultaneously, are discussed. The methodology is applied to simply supported beams using genetic algorithms to solve the optimization problem, since this problem involves several local minima. The objective function employed corresponds to the cost of the structural element, which includes the consumption of concrete, steel and formwork. The limit states are formulated according to the recommendations of the ABNT NBR 6118:2014 [1]. As a result, predominant characteristics were observed in the optimal sections, according to the limit states: for ULS, the sections presented more steel reinforcement; in the SLS predominance of concrete occurred; in ULS+SLS the optimal factors remained within the limit formed by ULS and SLS.

Keywords: optimization, reinforced concrete, limit states, genetic algorithms

1. INTRODUCTION

Due to the development of new technologies and the increase of market competitiveness, the search for more efficient and lower-cost designs has increased. At the same time, many reinforced concrete structures have been designed and built around the world, so that this construction system has become one of the most used. In this scenario, the importance of studies related to the design concept of reinforced concrete structures is valid.

To ensure the safety of a structure, the engineer must choose a design option which meets the normative checks related to its purpose. However, due to the large number of variables involved in the design of reinforced concrete structures, there are several different configurations that can meet the required conditions, with different costs and performances. Usually, the choice of a configuration is not simple, which makes it difficult to obtain an optimal design from traditional methods, that is, a design that is safe with the lower cost possible.

Several studies in the field of optimization of reinforced concrete structures have been developed in the last decades, with the objective of obtaining designs with optimal parameters, generally related to the cost of the structures ([2–9]). In this sense, many researchers have used genetic algorithms to optimize reinforced concrete structures ([10–18]).

However, there is a lack in studies that discuss such optimal characteristics and their relationships with normative verifications. Most current codes, including the Brazilian ABNT NBR 6118:2014 [1], are based on the concept of limit states. According to these codes, the structure must satisfy certain limit states simultaneously. Within this context, an analysis of the influence of such limit states on what would be the optimal configuration of reinforced concrete structures needs to be better evaluated, with the purpose of assisting the studies in project design.

Conceptually, a limit state is given by the situation (limit) from which a structural element no longer meets one of its design goals, in other words, when a structure fails to satisfy any of the purposes of its construction. The current Brazilian code establishes that the following limit states must be considered: Ultimate Limit State (ULS) and Serviceability Limit State (SLS). The ULS are related to any situation that determines the interruption, in whole or in part, of the use of the structure. The SLS are characterized by situations that, due to their occurrence, repetition or duration, generate structural effects that do not meet the conditions specified for the normal use of the structure, or indicate impairment of its durability [19].

In this sense, the present paper proposes to analyze the optimal configuration of reinforced concrete beams, through the minimization of its costs, considering two groups of constraints: the first is related to the ULS and the second to the SLS. The optimal characteristics of this structural element when subject to each group of constraints, individually, as well as to both groups, simultaneously, are discussed.

The main motivation of this paper is to expand the studies on the design of reinforced concrete structures through an analysis of the influence of the normative constraints on the optimal characteristics of this structures, in addition to contribute to the development of research in optimization of reinforced concrete structures by the development of a computational tool capable of optimizing their costs.

2. METHODOLOGY AND PROBLEM FORMULATION

The proposed problem consists in minimizing the cost of simply supported, rectangular section beams subjected to uniformly distributed loading. The solutions of the structures subject to the constraints of the ULS and the SLS, individually, are analyzed, as well as the structure subject to the constraints of both limit states simultaneously. Besides the constraints related to the limit states, in all cases, constructive constraints are also considered, that is, the optimum sections should check the following requirements: minimum longitudinal and transverse reinforcement rates; ductility conditions; concentrated stress in the center of gravity of the longitudinal reinforcements. All calculations follow the recommendations of the Brazilian code ABNT NBR 6118:2014 [1]. Figure 1 shows the configuration of the beams studied and the nomenclatures used.

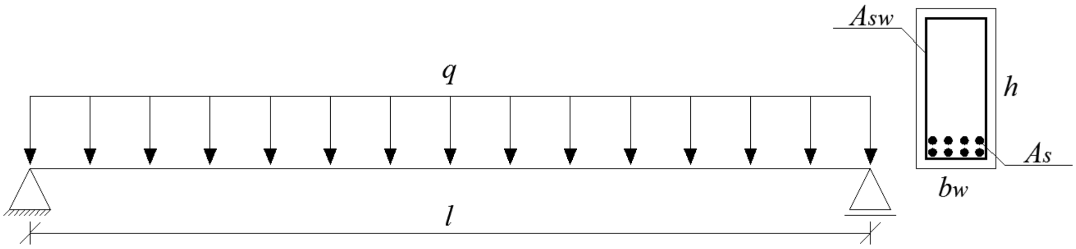

Figure 1. Beam design

2.1 Design variables

The design variables are the unknowns of the objective function, that is, the cross-sectional dimensions of the rectangular beam: width, b_w, and height, h; and the number of bars of the longitudinal, N_s, and transverse, N_{sw}, reinforcement. The variables are represented by the vector $\mathbf{x}$ described in Equation 1.

$$\mathbf{x} = [b_w, h, N_s, N_{sw}] \tag{1}$$

2.2 Objective function

In this paper, the objective function employed corresponds to the cost of the structural element, based on the cost of concrete volume, longitudinal and transverse reinforcement mass and formwork area. The unit costs adopted include materials and labor to construct the structure. The Equation 2 is the objective function used in the problem.

$$f(\mathbf{x}) = b_w \cdot h \cdot l \cdot C_c + A_s \cdot N_s \cdot l \cdot \rho_s \cdot C_s + A_{sw} \cdot N_{sw} \cdot l_{sw} \cdot \rho_{sw} \cdot C_{sw} + (2 \cdot h + b_w) \cdot l \cdot C_f \tag{2}$$

Where:
$\mathbf{x}$ = Vector of design variables;
C_c = Unit cost of concrete ($R\$/m^3$);
C_s = Unit cost of longitudinal reinforcement ($R\$/kg$);
C_{sw} = Unit cost of transverse reinforcement ($R\$/kg$);
C_f = Unit cost of formwork ($R\$/m^2$);
b_w = Beam width (m);
h = Beam height (m);
l = Beam length (m);
A_s = Cross-sectional area of one longitudinal reinforcement bar (m^2);
N_s = Number of longitudinal reinforcement bars;
ρ_s = Unit mass of steel of the longitudinal reinforcement (kg/m^3);
A_{sw} = Cross-sectional area of one transverse reinforcement bar (m^2);
N_{sw} = Number of transverse reinforcement bars;
l_{sw} = Length of one bar of the transverse reinforcement (m);
ρ_{sw} = Unit mass of steel of the transverse reinforcement (kg/m^3).

2.3 Constraints

The constraints imposed on the problem are represented by the vector $\mathbf{g}$ described by Equation 3, where n is the number of constraints $g_i(\mathbf{x})$ of the problem, with $i = 1, ..., n$. The restrictions were applied in the most requested sections, which in this case are in the middle or in the supports of the beam. The constraints adopted in this paper are described in the following.

$$\mathbf{g} = [g_1(\mathbf{x}), ..., g_n(\mathbf{x})] \tag{3}$$

2.3.1 ULS constraints

The ULS constraints are related to the strength capacity of the structural element section. In view of the applied load, the structure must withstand the design bending moment (M_{Sd}) and the design shear force (V_{Sd}). The internal forces are obtained from the normal ultimate combination of applied loads.

- Load-bearing capacity of a reinforced beam cross-section in bending:

The section of the element is safe with respect to the bending moment if it satisfies the constraint given by the Equation 4, where M_{Rd} is the ultimate (design) moment.

$$g_1(\mathbf{x}) = M_{Sd} - M_{Rd} \leq 0 \tag{4}$$

The M_{Rd} is calculated from Equation 5, obtained from the equilibrium of forces acting on the cross section, where f_{yd} is the design yield strength of longitudinal steel reinforcement, d is the effective depth (the distance from the extreme compression fibers of the concrete to the centroid of the reinforcement), λ is a parameter depending on the characteristic compressive strength of concrete (f_{ck}) e x is the neutral axis.

$$M_{Rd} = A_s \cdot N_s \cdot f_{yd} \cdot (d - 0.5 \cdot \lambda \cdot x) \tag{5}$$

The value of x is obtained from Equation 6, where α_c is a parameter of reduction of the compressive strength of concrete and f_{cd} is the design compressive strength of concrete.

$$x = \frac{A_s \cdot N_s \cdot f_{yd}}{\lambda \cdot \alpha_c \cdot f_{cd} \cdot b_w} \tag{6}$$

- Load-bearing capacity of a reinforced beam cross-section in shear:

The strength of the section with respect to the shear force is guaranteed if the Equations 7 and 8 are checked, where V_{Rd2} and V_{Rd3} are, respectively, the design shear strength of compressive diagonals of concrete and the design shear strength of traction diagonals (supplied by concrete and transverse reinforcement). Model I of the code is used to obtain shear strengths.

$$g_2(\mathbf{x}) = V_{Sd} - V_{Rd2} \leq 0 \tag{7}$$

$$g_3(\mathbf{x}) = V_{Sd} - V_{Rd3} \leq 0 \tag{8}$$

The value of V_{Rd2} is obtained from the Equation 9, where α_{v2} is a parameter which depends on the f_{ck}.

$$V_{Rd2} = 0.27 \cdot \alpha_{v2} \cdot f_{cd} \cdot b_w \cdot d \tag{9}$$

The value of V_{Rd3} is obtained from Equation 10, where f_{ctd} is the design tensile strength of concrete, s is the spacing between the transverse reinforcements and f_{ywd} is the design tension in the transverse reinforcement.

$$V_{Rd3} = 0.6 \cdot f_{ctd} \cdot b_w \cdot d + \frac{A_{sw}}{s} \cdot 0.9 \cdot d \cdot f_{ywd} \tag{10}$$

2.3.2 SLS constraints

In this paper, the limit state of excessive deformation is considered. It is represented by Equation 11, where a is the calculated deflection and a_{lim} is the maximum deflection allowed by the code.

$$g_4(\mathbf{x}) = a - a_{max} \leq 0 \tag{11}$$

In the evaluation of deflection, linear elastic behavior is considered for concrete and steel. Thus, the deflection in the beam is given by Equation 12, where α_f is a factor which considers the creep of concrete, F_{SLS} is the load obtained with the quasi-permanent load combination and $(E \cdot I)_{eq}$ is the equivalent flexural rigidity, which considers a weighting of the inertia of stages I and II, as well as the homogenized section.

$$a = (1 + \alpha_f) \cdot \frac{5 \cdot F_{SLS} \cdot l^4}{384 \cdot (E \cdot I)_{eq}} \tag{12}$$

3. OPTIMIZATION

Genetic algorithms are search algorithms, based on the mechanism of natural selection and natural genetics, developed in the 1970s by John Hollad at the University of Michigan [20]. The algorithm can be applied to solve problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, nondifferentiable or highly nonlinear.

These algorithms use some terms in analogy to natural genetics: the individual is a solution, which may or may not be viable; the population is the set of solutions; the chromosome is the coding that represents the individual; the gene is the coding that represents the variable; the allele is the value that the variable can assume [21].

In general, the algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals from the current population and uses them as parents to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution.

Genetic algorithms are composed of three main operators [16]:

- Reproduction (selection): This operator is used to select the set of individuals that will reproduce to generate the next population. This selection is made based on the fitness of each individual, determined from the objective function. Individuals with higher fitness are more likely to be chosen. The suitability of an individual is affected by violation of the constraints of the problem, and to introduce viability into the fitness of a solution, penalties are taken when a solution does not meet some constraint.
- Crossover: This operator is used to propagate the positive characteristics of the fittest individuals of the population (selected by the reproduction operator), by means of the exchange of segments of information between them, in order to originate new individuals.
- Mutation: The mutation operator is used to bring about random changes in the population. At this stage, characteristics of individuals are altered, thus adding variety to the population. This operation is carried out in order to search for unexplored areas and avoid premature convergence in an optimal local solution. At the same time, a higher frequency of this operator can destroy the important information contained in the population. Thus, the mutation occurs only in a small part of the population.

In this paper, a preprogrammed genetic algorithm routine, contained in the MatLab software, is used. Figure 2 presents a flowchart of the algorithm.

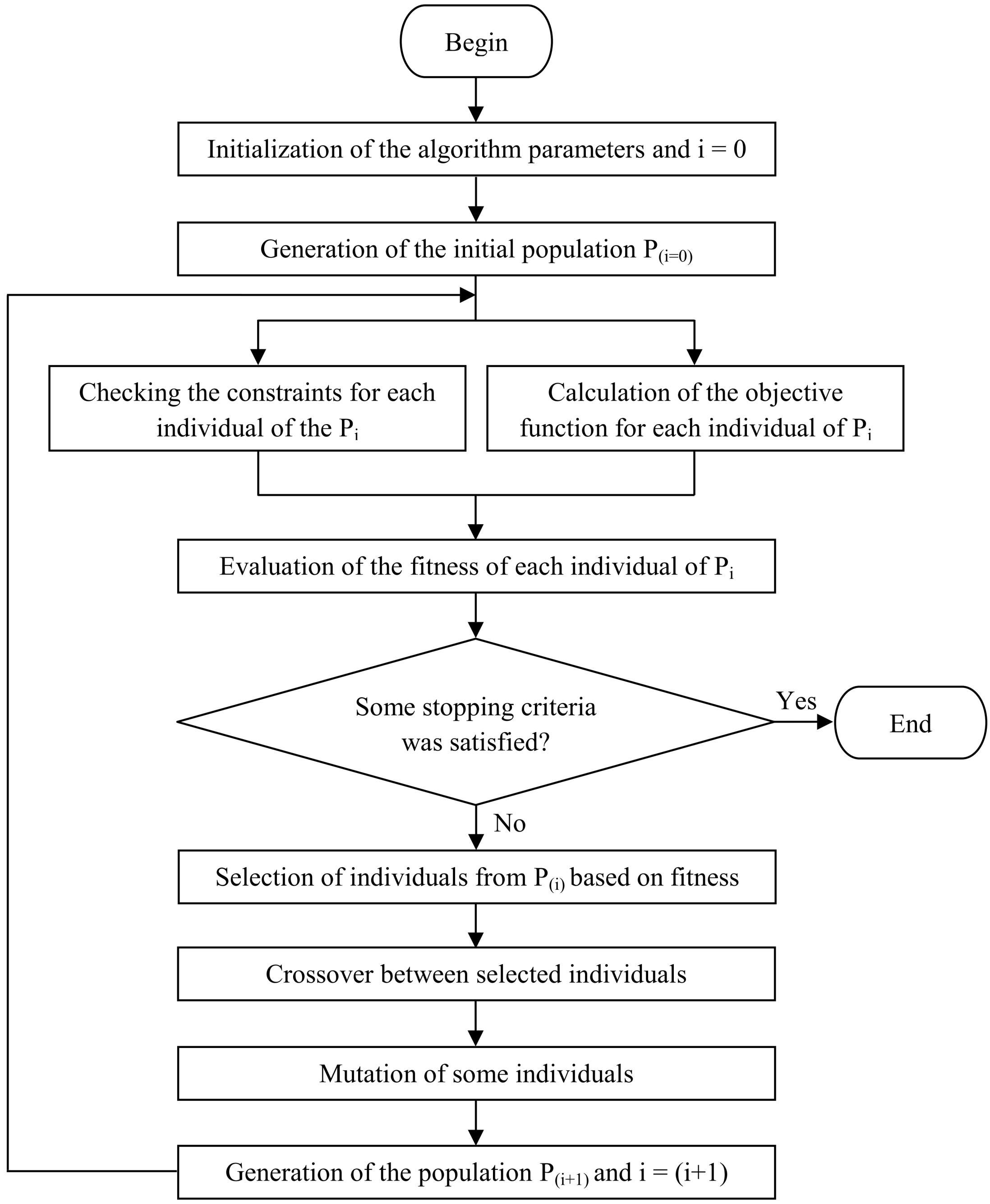

Figure 2. Flowchart of the optimization algorithm

4. NUMERICAL EXAMPLE

The example consists of a beam from a residential design, presented highlighted (B_4) in Figure 3. The input data used in the example is shown in Table 1 and the values of unit costs are taken from [22]. In this example, four different loading levels are considered: 40%, 60%, 80% e 100% of the total load applied to the beam (F_{ULS} e F_{SLS}). It should be noted that the load due to the weight of the beam (Pp) is also considered, that is, in addition to the loads already mentioned, at each iteration the weight of the structure is updated. The variables b_w and h are said to be continuous within the intervals [0.12 m; 0.30 m] and [0.20 m; 0.60 m], respectively. The variables N_s and N_{sw} are discretized in sets [2 3 4 5 6 7 8] and [51 35 26 21 18], respectively.

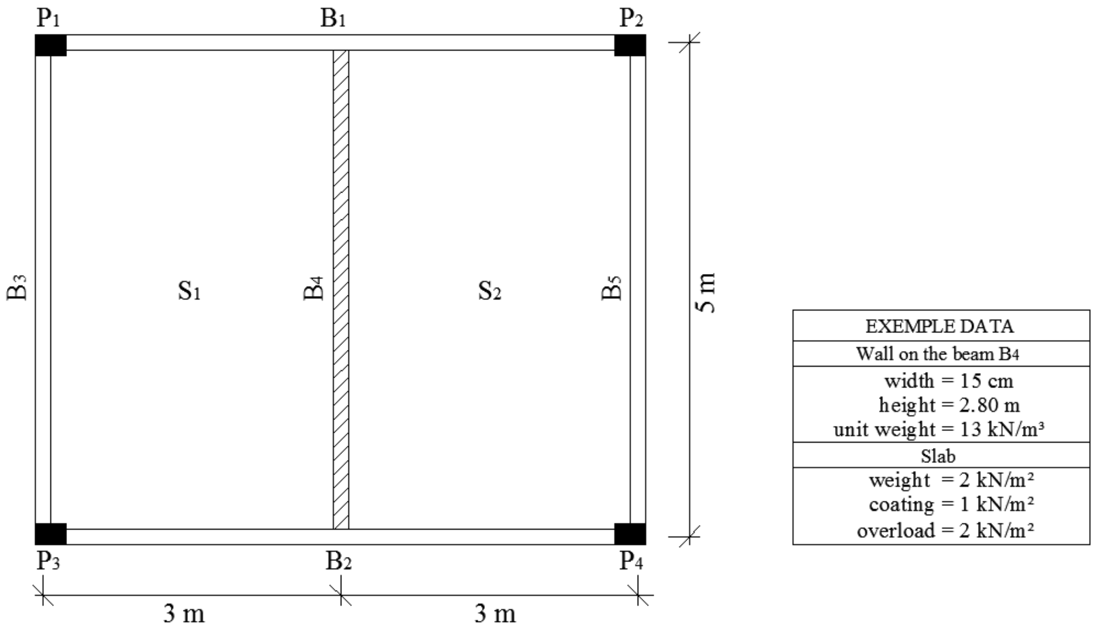

Figure 3. Part of the design with emphasis on the analyzed beam (B_4)

Table 1. Input data

Data		Value	Unit
E_s	Modulus of elasticity of longitudinal steel reinforcement	210,000	MPa
ρ_s	Unit mass of steel of the longitudinal reinforcement	7,850	kg/m^3
ρ_c	Unit weight of reinforced concrete	25	kN/m^3
f_{yk}	Characteristic yield strength of longitudinal steel reinforcement	500	MPa
f_{ck}	Characteristic compressive strength of concrete	25	MPa
c	Cover to reinforcement	2.5	cm
F_{ULS}	Load - Normal ultimate combination	28.66 + Pp	kN/m
F_{SLS}	Load - Quasi-permanent load combination	16.87 + Pp	kN/m
ϕ_s	Nominal diameter of longitudinal reinforcement bar	12.5	mm
ϕ_{sw}	Nominal diameter of transverse reinforcement bar	6.3	mm
C_c	Unit cost of concrete	401.60	$R\$/m^3$
C_s	Unit cost of longitudinal reinforcement	5.59	$R\$/kg$
C_{sw}	Unit cost of transverse reinforcement	6.08	$R\$/kg$
C_f	Unit cost of formwork	53.89	$R\$/m^2$

Note: The properties of the steel of the transverse reinforcement are the same as those of the steel of the longitudinal reinforcement.

4.1 Optimization results

Table 2 presents the results of the optimization for all loading cases. These results can be visualized in Figure 4.

In all cases, it is noticed that the higher the load applied, the higher the cost of the structure, as expected, and that in cases where the limit states are considered individually, the optimal costs are lower than in those cases where both limit states are considered simultaneously. Also in terms of costs, the predominant input in all cases (ULS, SLS and ULS+SLS) is the formwork, which reaches 60% of the total optimum cost, followed by the steel reinforcement for the ULS and the concrete for

Table 2. Results

Limit State	Cost [R\$]				Optimum Parameters			
	Concrete	Steel	Formwork	Total	b_w $[m]$	h $[m]$	N_s	N_{sw}
Loading Case I								
ULS	83.04 (19.79%)	118.73 (28.29%)	217.93 (51.92%)	419.70 (100%)	0.12	0.34	3	35
SLS	100.21 (22.65%)	87.38 (19.75%)	254.81 (57.60%)	442.40 (100%)	0.12	0.41	2	26
ULS + SLS	95.37 (21.01%)	112.94 (24.88%)	245.55 (54.10%)	453.86 (100%)	0.12	0.40	3	26
Loading Case II								
ULS	93.52 (19.72%)	139.27 (29.37%)	241.46 (50.91%)	474.25 (100%)	0.12	0.39	4	26
SLS	118.49 (23.81%)	85.46 (17.18%)	293.61 (59.01%)	497.56 (100%)	0.12	0.48	2	21
ULS + SLS	112.43 (22.16%)	111.17 (21.92%)	283.65 (55.92%)	507.25 (100%)	0.12	0.47	3	21
Loading Case III								
ULS	115.14 (21.18%)	138.79 (25.53%)	289.64 (53.29%)	543.57 (100%)	0.12	0.48	4	21
SLS	133.58 (24.57%)	84.17 (15.48%)	325.99 (59.95%)	543.74 (100%)	0.12	0.54	2	18
ULS + SLS	119.41 (21.38%)	139.91 (25.05%)	299.29 (53.58%)	558.61 (100%)	0.12	0.50	4	21
Loading Case IV								
ULS	119.76 (20.41%)	166.93 (28.45%)	300.16 (51.15%)	586.85 (100%)	0.12	0.50	5	21
SLS	144.51 (24.62%)	87.04 (14.83%)	355.53 (60.56%)	587.08 (100%)	0.12	0.60	2	18
ULS + SLS	126.18 (20.72%)	168.58 (27.68%)	314.34 (51.61%)	609.09 (100%)	0.12	0.52	5	21

the SLS. It is emphasized that the reuse of the formwork is not considered, which explains the great impact of this input on the total cost of the structure.

For the optimization that considers only the constraints of the ULS, it is seen that the optimal value of N_s, in all loading cases, is equal to or greater than the optimal values of the other two cases of optimization (SLS and ULS+SLS). The application of the constraint g_1 causes an increase of longitudinal reinforcement, which can be understood by the analysis of the Equation 5. Note that N_s is proportional to M_{Rd}, that is, the larger the total longitudinal steel area, the greater the resistance of the section in relation to the bending moment. The value of the variable N_{sw} also tends to be higher in the ULS, given the constraint g_3, where the value of V_{Rd3} increases as the amount of transverse reinforcement increases. Other variables also influence the constraints g_1, g_2 and g_3, such as h, where the higher its value, the greater are M_{Rd}, V_{Rd2} and V_{Rd3}. Therefore, it is understood that the configuration of the optimal section for this limit state seeks to find an equilibrium among h, N_s and N_{sw}, so that the final cost is minimal and meets the constraints. However, relative to the other two cases of optimization (SLS and ULS+SLS), it is observed that the optimal sections of the ULS tend

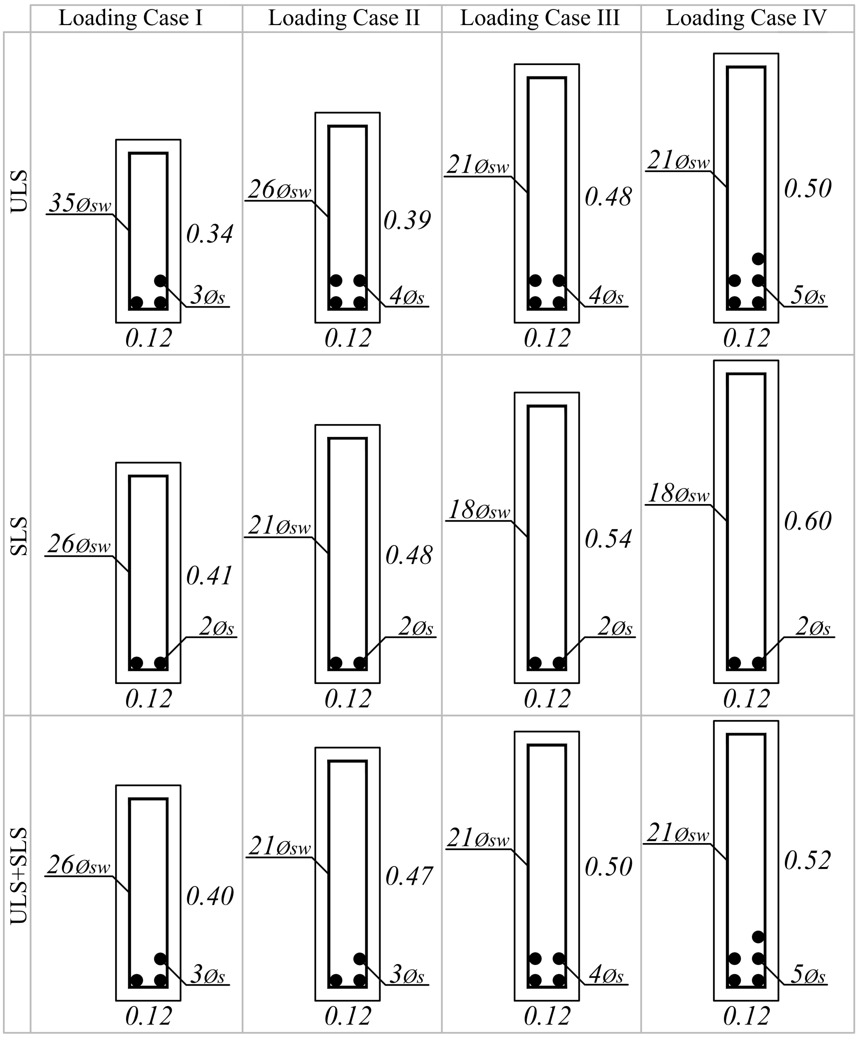

Figure 4. Detailing the optimal sections

to be more reinforced, with a smaller area of concrete.

In reference to the optimization that considers only the constraints of the SLS, it is noted that the optimal value of h, in all loading cases, is greater than in the other two cases of optimization (ULS and ULS+SLS). The constraint g_4, which governs this limit state, has great influence on the inertia of the cross-section of the beam. This fact can be understood from Equation 12, in which the only parameter that changes according to the design variables is the inertia of the section. Since h is an influential design variable in inertia, that is, the higher the section the greater its inertia, the optimum section for the SLS tends to have height as much as is necessary to counter the deflection of the beam. Despite of the fact that the inertia adopted consider the homogenized section, which takes into account the amount of longitudinal reinforcement, which in its turn depends on N_s, the optimum section found is predominantly concrete, because in SLS, the optimal value of N_s is the minimum allowed. Therefore, the optimum sections of the SLS tend to have less steel and more concrete when compared to the optimal sections of the ULS and ULS+SLS.

The values of the variables for the optimal sections that consider both limit states remained within the limits between the optimal of the ULS and the SLS. The values of h are higher than those of the ULS, due to the insertion of the maximum deflection constraint. Given this increase in height, the values of N_s and N_{sw} in the ELU+ELS, in some loading cases, decreased in comparison to the ULS.

The optimal width of the beam was similar in all cases studied, approximately 12 cm. It does not have as much influence on the strength and inertia of the cross section as height, and the increase of its value increases the cost of formwork and concrete, which justifies its minimum value.

For better visualization of the analyzes, Figures 5 and 6 are presented. Note that for all loading cases, the optimal cost of the beam increases from the ULS to the SLS, until the higher cost is obtained when considering both limit states simultaneously. It is also noticed that, for lower loads, the optimal height of the ULS+SLS section is similar to that of the SLS, and for higher loads, the optimum height approaches the ULS.

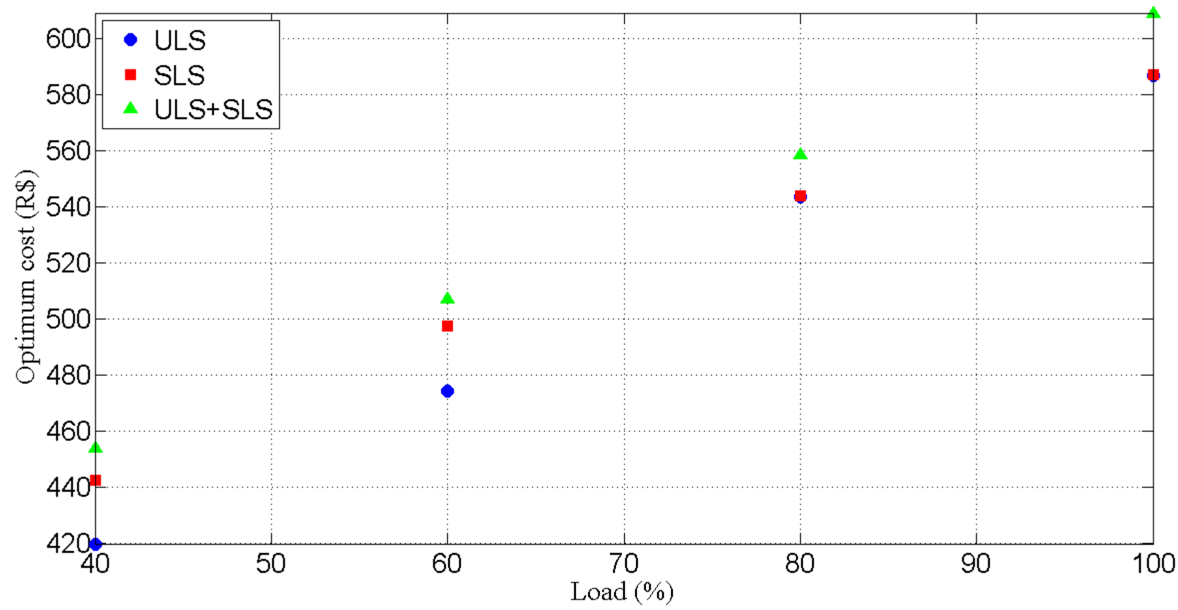

Figure 5. Relation between the applied load and the optimum cost

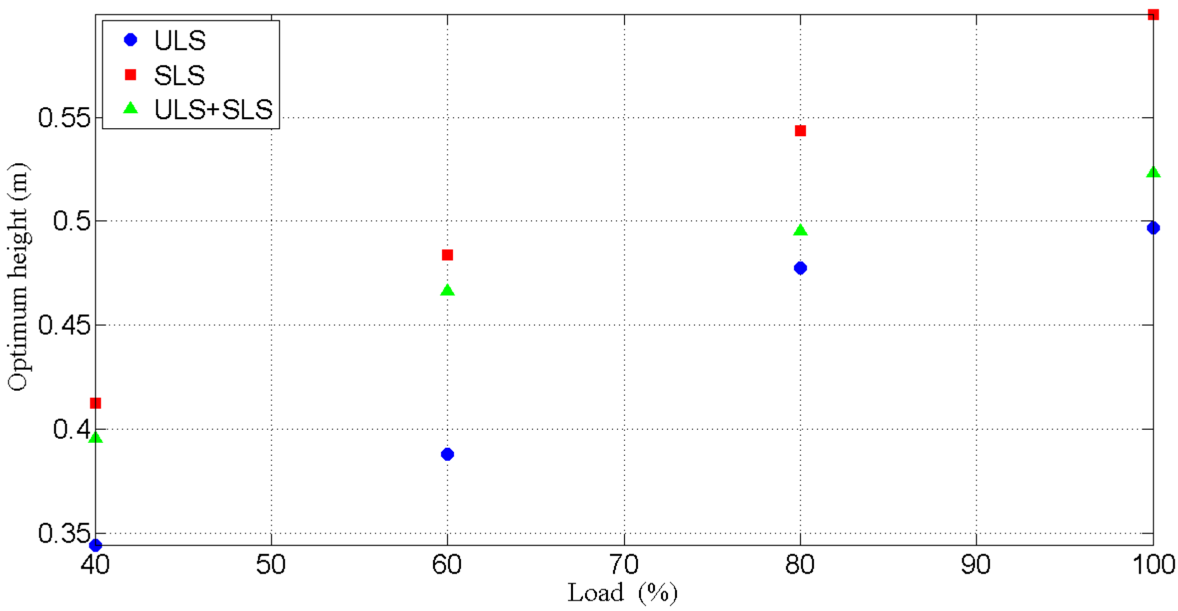

Figure 6. Relation between applied load and optimum height

5. CONCLUSIONS

This paper presented an optimization scheme for reinforced concrete beams, based on the ultimate and serviceability limit states, in which genetic algorithms were applied. The purpose of the paper was to verify the optimal characteristics of the structure for each limit state individually and for both limit states simultaneously. Four loading cases were considered and the optimum sections presented predominant characteristics when comparing the three cases of optimization (ULS, SLS and ULS+SLS): the optimal sections for the ULS were more reinforced and with smaller areas of concrete; in the SLS case, the optimal sections presented the smaller amount of bars and larger heights, which results in sections that were less reinforced and with greater area of concrete; when both limit states were considered, an intermediate optimal solution between the ULS and SLS was found. It should be noted that no optimal section for ULS met the SLS constraints, the reverse being true as well, so that the cost of ULS+SLS is the highest in the four loading cases studied. The input with preponderant cost in all cases was the formwork, followed by the steel reinforcement for the ULS and the concrete for the SLS, which agrees with the preponderant characteristics of the optimal sections of each limit state. It is concluded that the optimal factors of the sections for each limit state are distinct and conflicting with each other, which results in predominant characteristics for the beams, according to the limit states that must be verified.

6. ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from FAPESC and CNPq.

REFERENCES

[1] ABNT, Rio de Janeiro (2014). NBR 6118: Projeto de estruturas de concreto - procedimento.

[2] Gerlein, M. A. and Beaufait, F. W. (1980). "An optimum preliminary strength design of reinforced concrete frames." Computers & Structures, 11:515–524.

[3] Kanagasundaram, S. and Karihaloo, B. L. (1991). "Minimum-cost reinforced concrete beams And columns." Computers & Structures, 41:509–518.

[4] Adamu, A. and Karihaloo, B. L. (1995a). "Minimum cost design of RC frames using the DCOC method - Part I: Columns under uniaxial bending actions." Structural Optimization, 10:16–32.

[5] Adamu, A. and Karihaloo, B. L. (1995b). "Minimum cost design of RC frames using the DCOC method - Part II: Columns under biaxial bending actions." Structural Optimization, 10:33–39.

[6] Kwak, H. G. and Kim, J. (2008). "Optimum design of reinforced concrete plane frames based on predetermined section database." Computer-Aided Design, 40:396–408.

[7] Nigdeli, S. M. and Bekdas, G. (2016). "Optimum design of RC continuous beams considering unfavourable live-load distributions." KSCE Journal of Civil Engineering, pages 1–7.

[8] Zaforteza, I. P., Yepes, V., Hospitaler, A., and Vidosa, F. G. (2009). "CO2-optimization of reinforced concrete frames by simulated annealing." Engineering Structures, 31:1501–1508.

[9] Camp, C. V. and Huq, F. (2013). "CO2 and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm." Engineering Structures, 48:363–372.

[10] Coello, C. A. C., Christiansen, A. D., and Hernández, F. S. (1997). "A simple genetic algorithm for the design of reinforced concrete beams." Engineering with Computers, 13:185–196.

[11] Koumousis, V. K. and Arsenis, S. J. (1998). "Genetic algorithms in optimal detailed design of reinforced concrete members." Computer-Aided Civil and Infrastructure Engineering, 13:43–52.

[12] Rajeev, S. and Krishnamoorthy, C. S. (1998). "Genetic algorithm - based methodology for design optimization of reinforced concrete frames." Computer-Aided Civil and Infrastructure Engineering, 13:63–74.

[13] Rafiq, M. Y. and Southcombe, C. (1998). "Genetic algorithms in optimal design and detailing of reinforced concrete biaxial columns supported by a declarative approach for capacity checking." Computers & Structures, 69:443–457.

[14] Leps, M. and Sejnoha, M. (2003). "New approach to optimization of reinforced concrete beams." Computers & Structures, 81:1957–1966.

[15] Camp, C. V., Pezeshk, S., and Hansson, H. (2003). "Flexural design of reinforced concrete frames using a genetic algorithm." Journal of Structural Engineering, 129(1):105–115.

[16] Govindaraj, V. and Ramasamy, J. V. (2005). "Optimum detailed design of reinforced concrete continuous beams using Genetic Algorithms." Computers & Structures, 84:34–48.

[17] Sahab, M. G., Ashour, A. F., and Toropov, V. V. (2005). "Cost optimisation of reinforced concrete flat slab buildings." Engineering Structures, 27:313–322.

[18] Kwak, H. G. and Kim, J. (2009). "An integrated genetic algorithm complemented with direct search for optimum design of RC frames." Computer-Aided Design, 41:490–500.

[19] ABNT, Rio de Janeiro (2003). NBR 8681: Ações e segurança nas estrututras - procedimento.

[20] Goldberg, D. E. (1989). Genetic algorithms in search, optimization & machine learning. Addison-Wesley.

[21] Lima, M. L. R. (2011). Otimização topológica e paramétrica de vigas de concreto armado utilizando algoritmos genéticos. Master's thesis, Universidade de Sâo Paulo, São Paulo.

[22] SCO, Rio de Janeiro (2016). Composição de itens de serviço da prefeitura.

RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.