XL CILAMCE
IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING
NOVEMBER 11-14, 2019
Praiamar Natal Hotel & Convention
Natal, RN-BRAZIL

# DEVELOPMENT OF AN AIDING TOOL FOR THE OPTIMAL DETAIL OF ACTIVE REINFORCEMENT USING GENETIC ALGORITHM

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**Abstract.** The aim of this paper is to present the development of an auxiliary tool for the optimal detail of active reinforcement on a prestressed concrete section. To achieve it, the methodology considers normative requisites and the tension required at the most critical section of the beam. The problem of optimization seeks to minimize the volume of steel while satisfying the conditions of minimum cover and spacing between reinforcement cables. Design variables are the number of strands per cable and the position of each cable within cross section. Due to the nature of the variables and the constraints involved, genetic algorithm seems to be the most suitable optimization procedure. Hence, the proposed methodology is implemented using the native implementation of genetic algorithm of MATLAB, a broadly used computer program in academy. The developed tool allows to detail different sections, since it treats the cross section as a general polygon. Thereby, it allows exploitation of new sections for future projects, as well as assisting in the time of design. It is worth mentioning that a complete automated prestressed concrete executive project is still far down the road. Numerical examples are analyzed to demonstrate the efficiency of the presented tool and to illustrate it's usage in a actual life design process.

**Keywords:** Prestressed Concrete, Optimal Detailing, Genetic Algorithm

## 1 Introduction

Concrete is an ancient material that was already known by the time of the Roman Empire. It is formed by a mixture of cement, water and aggregated. It was used as a mass to lay bricks, among other functions. In the nineteenth century the material regained attention, once realized that it had some advantages over the materials used at that time. Among the advantages of concrete, it is worth mentioning that it is moldable and have workability when wet, it is resistant to loads and fire, and it increases the service life of the structure after cured.

Despite all these advantages this material is fragile and works better resisting compression than traction. To cope with that, steel is added to concrete in regions where tensile stresses are predominant. The result is a material of good strength and ductility, if properly designed. The steel might even be prestressed, allowing the compression strength of concrete to be more effective in bending. This constructive method consisting of the application of tension in steel cables in traction regions of the structure before or after the curing of the concrete and without or with bonding is often referred to as prestressed concrete.

The advantages of this type of construction are: the execution of spans larger than the reinforced concrete; the reduction of deformations and crack opening; a shorter time in implementation of construction; saving concrete, since it uses steel and high-strength concrete; the reduction of the weight of the structure, since it can build with more slenderness; and other more. However, there are also disadvantages such as the high price of steel and the need for skilled labor. It can be used in a variety of ways, such as in large slabs and beams, foundations, anchored walls, dams, bridges, and recovery of compromised structures.

The prestressed concrete design is carried out through the concrete adopted, the active and passive reinforcement and type of execution – initial or posterior bonding or without bonding. In addition, it is necessary to take into account the class of environmental condition. Then the cross-section of the structure is defined, which furnishes the structural self-weight and its flexural rigidity. After that it is necessary to pre-dimension the active reinforcement.

In the process of designing prestressed concrete structures, the tension that must be provided to concrete is calculated first to match the specified limits of designing standards. Subsequently, it is needed to find an active reinforcement detail that provides the required tension and meets the coverage and spacing requirements of designing codes. However, this process is manual and laborious. In general, it starts with simplifying hypothesis, which, when missed, need to be changed leading to an iterative process.

This process is currently solved, only, from an initial estimate based on the experience of the designer. Thus, it is an unfavorable process to the new designers and make the exploitation of innovative sections difficult. In case of convergence, there is a detail that serves the required tension. However, this is only one possible outcome, and there is no guarantee that is the best. Thus, a detail methodology more automated and that seek out the less consumption of materials would reduce the time demanded for this step significantly and would provide generally more economic solutions and with reduction of rework.

In order to decide the method of optimization to be used to produce this tool, some methods were checked such as the gradient-based method, meta-heuristics, natural computing and genetic algorithm, which was chosen because in addition to the ability to solve problems of optimization with discrete variables, they work with discontinuous functions and not differentiable.

This article will introduce the development of an automated tool to support the detailing step of the active reinforcement with full or limited prestressing, with posterior adhesion using the genetic algorithm. Specifically, for a given section and its prestressing tension requirements known, seeking the most economical detailing in relation to the volume of steel, avoiding the manual process and rework.

## 2 Prestressed Concrete

Prestressed concrete structures must agree the requirements of ultimate limit state (ULS) and serviceability limit state (SLS). However, the information required to verify those limit states is only available after the structure is completely detailed. Therefore, is a common practice to estimate some of the values involved to encounter the missing ones. In prestressed concrete design, commonly, the pre-dimensioning of active reinforcement begins by calculating the total prestress required to meet the SLS's at infinity time (when long-term losing process have already been completed).

The SLS equation may, in general, be written as

$$\sigma_F + \sigma_{P^c_\infty} \leq \overline{\sigma}_c\,, \tag{1}$$

in which, $\sigma_F$ is the stress due to the specified load combination, $\sigma_{P^c_\infty}$ is the stress caused in concrete by prestressing at infinity time and $\overline{\sigma}_c$ is the limit stress related to each SLS.

From Eq. (1) it is possible to determine the maximum prestressed required, hereinafter $(x_t, y_t)$ is referred to as the point within a beam in which the prestressed required is maximum. This prestress may also be written, according to classic solid mechanics, as

$$\sigma_{P^c_\infty} = \frac{P^c_\infty}{A} - \frac{M_{P^c_\infty} y_t}{I}\,, \tag{2}$$

in which, $P^c_\infty$ is the prestress force at concrete at infinity time, $A$ is the cross-section area, $M_{P^c_\infty}$ is the bending moment caused by prestress eccentricity and $I$ is the cross-section moment of inertia. Is important pointing out that Eq. (2) is also an approximation since it does not represent the actual prestress in statically determined structures.

The prestress force $P^c_\infty$ may be calculated as

$$P^c_\infty = -P_\infty = -nN\,p_\infty = -nN\,\eta_\infty\,p_i\,, \tag{3}$$

in which, $P_\infty$ is the prestress force at steel at infinity time, $n$ is the number of cables, $N$ is the number of strands per cable, $p_\infty$ is the force at infinity time per strand, which is obtained estimating the long-term prestress losses through coefficient $\eta_\infty$ and through the initial prestress force per strand $p_i$ [1]. The bending moment due to prestress force is given by

$$M_{P^c_\infty} = -\sum_{k=1}^{n} P^c_{\infty,k} y_k\,, \tag{4}$$

in which $P^c_{\infty,k}$ is the prestress force at concrete at infinity time of $k$-th cable and $y_k$ is its position. Since all cables have the same number of strands, the force in each of them is considered equal, therefore, Eq. (4) becomes

$$M_{P^c_\infty} = -P^c_\infty e\,, \tag{5}$$

in which, $e$ is the eccentricity of an equivalent cable. This eccentricity $e$ is given by

$$e = \frac{\sum_{k=1}^{n} y_k}{n}\,. \tag{6}$$

### 2.1 Representation of the cross-section

In order to make the algorithm able to handle prestressed concrete cross-section of any shape and in the presence, or not, of inner holes, the external boundary and each hole are represented by polygons. The information of each polygon are storied as matrices of shape $(m_k, 2)$, $m_k$ being the number of vertices. Each row represents a vertex, storing in the columns its $x$ and $y$ coordinates. The vertices must be ordered counterclockwise for the boundary, and clockwise for the holes. For example, a box cross-section with $20\text{cm}$ width, $40\text{cm}$ height and $5\text{cm}$ thickness, shown in Fig. 1 with an adopted coordinate system, would have its external boundary represented as in Table 1 and its hole storied as in Table 2.

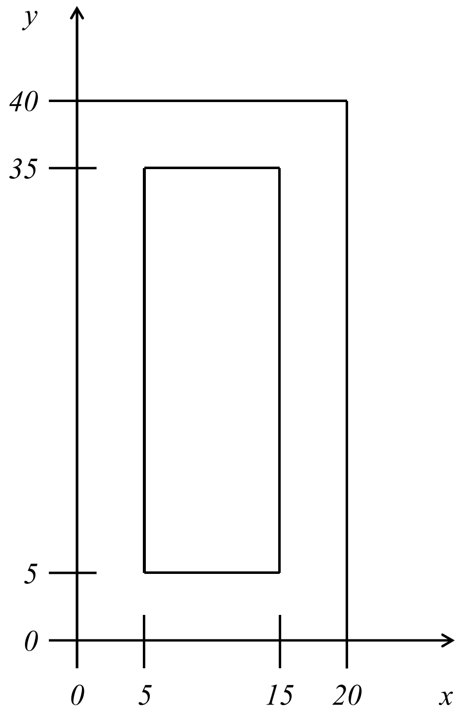


Figure 1. Box cross-section within coordinate system

Table 1. Matrix representing boundary's polygon

| | |
|---|---|
| 0 | 0 |
| 20 | 0 |
| 20 | 40 |
| 0 | 40 |

Table 2. Matrix representing hole's polygon

| | |
|---|---|
| 5 | 5 |
| 15 | 5 |
| 15 | 35 |
| 5 | 35 |

### 2.2 Calculation of cross-section properties

The general formula for the area $A$ and first and second moment of inertia $Q$ and $I$ may be found using Green's theorem for performing a bound integral instead of a domain integral. Therefore, one may find

$$A = \frac{1}{2}\sum_{i=1}^{m}(x_i y_{i+1} - x_{i+1} y_i)\,, \tag{7}$$

$$Q_x = \frac{1}{6}\sum_{i=1}^{m}(x_i + x_{i+1})(x_i y_{i+1} - x_{i+1} y_i)\,, \tag{8}$$

$$Q_y = \frac{1}{6}\sum_{i=1}^{m}(y_i + y_{i+1})(x_i y_{i+1} - x_{i+1} y_i)\,, \tag{9}$$

$$I_{xx} = \frac{1}{12}\sum_{i=1}^{m}(y_i^2 + y_i y_{i+1} + y_{i+1}^2)(x_i y_{i+1} - x_{i+1} y_i)\,, \tag{10}$$

$$I_{yy} = \frac{1}{12}\sum_{i=1}^{m}(x_i^2 + x_i x_{i+1} + x_{i+1}^2)(x_i y_{i+1} - x_{i+1} y_i)\,, \tag{11}$$

$$I_{xy} = \frac{1}{24}\sum_{i=1}^{m}(x_i y_{i+1} + 2x_i y_i + 2x_{i+1} y_{i+1} + x_{i+1} y_i)(x_i y_{i+1} - x_{i+1} y_i)\,. \tag{12}$$

### 2.3 Verification of coverage and spacing

Coverage is the smaller distance between the interface between concrete and steel and the free surface of concrete. That distance is often lower bounded by design standards so that concrete effectively protects the steel from corrosion and fire exposure. That limitation is taken into the algorithm as a constraint in the optimization process. Hence, the coverage must be evaluated in the cross-section polygon. Coverage constraint may be written as

$$d - \frac{\phi}{2} \geq \bar{c}\,, \tag{13}$$

in which, $d$ is the signed distance between the cable's center and the boundary or hole, $\phi$ is the cable external diameter, and $\bar{c}$ is the minimum cover by design code.

The sign in $d$ must be positive if the point is inside the polygon and negative otherwise. The algorithm for computing $d$ is divided in two part, one calculates its module and the other its sign, so that

$$d = \text{sign}\,(d)\,\|d\|\;. \tag{14}$$

The distance $\|d\|$ is calculated through Algorithm 1.

**Algorithm 1:** Calculation of unsigned distance

```
Input: point, boundary, holes
Output: Smallest distance between point and the cross-section
min_dist ← distancePointPolygon(point, boundary);          // Algorithm 2
foreach hole do
    dist ← distancePointPolygon(point, hole);              // Algorithm 2
    if dist ≤ min_dist then
        min_dist ← dist
    end
end
```

**Algorithm 2:** distancePointPolygon

**Input:** *point*, *polygon*
**Output:** Smallest distance between point and polygon

```
i ← 1;
segment = polygon(i);
min_dist← distancePointSegment(point, segment);
while i ≤ number of segments in polygon do
    i←i+1;
    segment = polygon(i);
    dist← distancePointSegment(point, segment);
    if dist≤min_dist then
        min_dist←dist
    end
end
```

In Algorithm 2, function *distancePointSegment* is called, its implementation consists of returning the smallest distance between a point and a segment. This requires basic math and, hence, the algorithm is suppressed. The sign function in Eq. (14) is declared to determine whether a cable is inside or outside the cross-section polygon. This is accomplished using the ray casting algorithm, which according to Hughes et al. [2] "Ray casting is a direct process for answering an intersection query". From the point of interest, an ray is traced in any direction counting the number of intersections it has with the polygon. If the number of intersections is even the point is outside polygon, thus negative sign is returned. On the other hand, if the number of intersections is odd, the point is inside, and positive sign is returned.

Spacing is the distance that must be left free between prestressing cables. In general, design codes prescribe bounds on the horizontal spacing $a_h$ and the vertical displacements $a_v$ [3]. That condition may be verified as follows. Given two cables, cable $i$ centered at $(x_i, y_i)$ with external diameter $\phi_i$ and cable $j$ centered at $(x_j, y_j)$ with external diameter $\phi_j$, compute

$$dx_{ij} = |x_j - x_i|\,, \tag{15}$$

$$dy_{ij} = |y_j - y_i|\,, \tag{16}$$

then, define

$$d_{ij} = \max\left(dx_{ij}, dy_{ij}\right)\ , \tag{17}$$

form which the spacing condition is given by

$$d_{ij} - \frac{\phi_i}{2} - \frac{\phi_j}{2} \geq \begin{cases} a_h, & \text{if } d_{ij} = dx_{ij} \\ a_v, & \text{if } d_{ij} = dy_{ij} \end{cases}\ . \tag{18}$$

## 3 Genetic Algorithm

The genetic algorithm (GA) was used in the development of this tool because it is a method suitable for finding the global optimal of the problem with multiple local optimum solutions. Additionally, GA is efficient in structural problems that can often be complex de Leon F. de Carvalho [4]. For its implementation MATLAB has been used, a computational software, broadly used in the academic community. Also, MATLAB's GA implementation, allows for easy user customization.

The optimization using this algorithm follows a predetermined set of steps, as illustrated in Fig. 2. The first part consists of the problem setup. The first step is the problem acknowledgement, in which all information about the problem is gathered. The second step is the solution coding, in this step the chromosome is defined. It consists of the coding representation of all possible solutions to the problem.

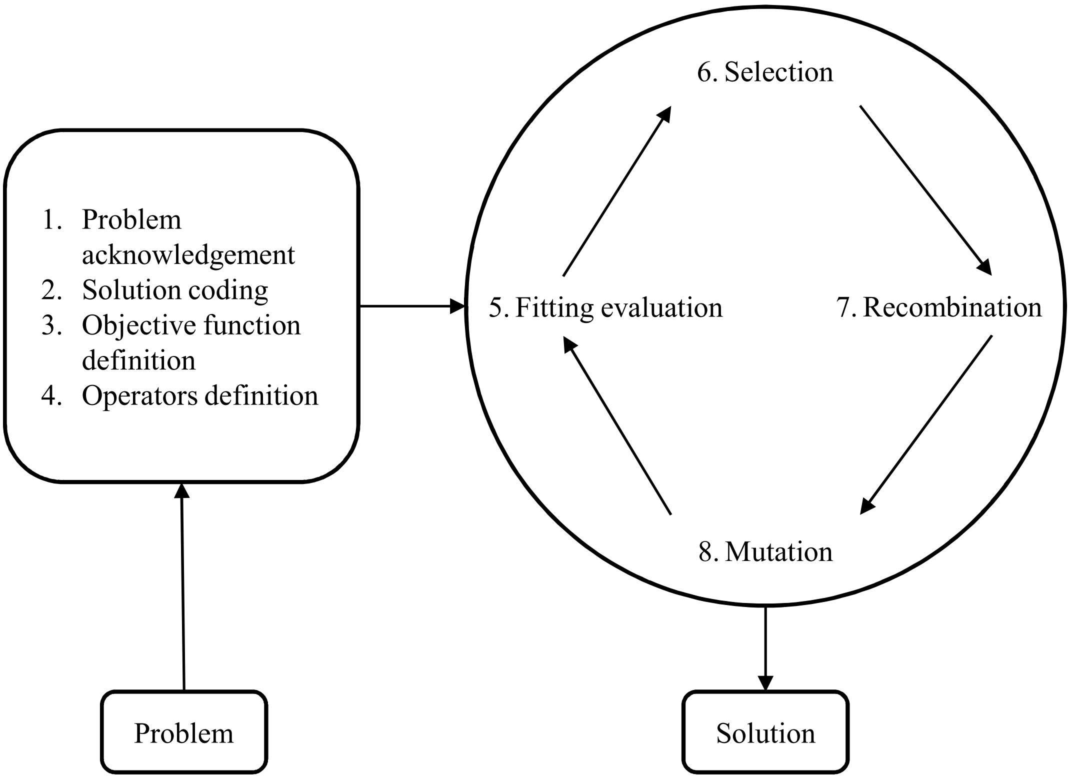


Figure 2. Box cross-section within coordinate system

The third step is the definition of the objective function, which tells the algorithm the best between two solutions. The fourth step consists of the operators definition which drives the formation of new populations, and the formation of the initial population.

The second part of the algorithm performs the optimization altering the current population and forming new ones in the seek of the global optima. Four main steps are worth mentioning: fitting evaluation, in which the objective function is evaluated for each individual; selection, which is the selection of individuals for reproduction, the most better fitted are the more likely to generate descendents; recombination, is the step where the chromosomes of the selected parents are mixed up together to form, in general, two new individuals; and mutation, which is the randomly change in the chromosome of a recent-generated individual. The algorithm proceeds within this cycle until it hits the end of pre-established number of generations. It is also common for the algorithm to stop before that, if it hits a stalling point, this is usually measured as the number of generations without finding a new best solution.

### 3.1 Representation of the Algorithm and Operators

In order to represent the algorithm the chromosome in the classical representation of GA is decoded as a vector of fixed size. Each position of this vector called a gene. The chromosome adopted in this work must represent any possible detailing of prestressed concrete section. First, it is necessary to define the maximum possible number of cables in the solution $n$, thus the chromosome may have fixed length. Then, to make it possible for the solution to have less cables than the maximum defined value, a flag indicating if each cable is to be considered in the detailing is added. A flag is a 1 or 0 variable, if its value is 1, the cable is on the detailing.

In Fig. 3, the genes, represented in each box, are: N the number of strands per cable; $f_i$ the flag of $i$-th cable; and $x_i$ and $y_i$ are $x$ and $y$ coordinates of the $i$-th cable. Here, $i$ = 1, ..., $n$ and $n$ is the total possible number of cables. For each gene there is a set of possible values, for instance the number of strands per cable are limited to manufacturer's specifications; the flag, as aforementioned, may be valued to 0 or 1; and $x$ and $y$ is restricted to lie inside the bounding box of the cross-section polygon.

In addition to the representation of the chromosome, some aspects of the GA may be addressed so that the algorithm performs well, prompting good results and reducing computational costs. The most discussed factors in genetic algorithms are population size, crossover rate, mutation rate and number of generation. Furthermore, for the sake of performance, operators may also have to be addressed. They drive the algorithm through the search space towards the solution. Among them it is worth mentioning initial population, crossover function and mutation function. A brief discussion of each is presented in the sequel.

The population size is the number of individuals, which means, in this case, different detailing that are evaluated at each generation. Since each individual is evaluated for the fitness function and constraints, the larger its value the longer the algorithm takes. On the other hand, a small population size may not grant enough coverage of search domain, commonly leading to a local optimum. For all numerical experiments carried in the development of this work, a population size of 50 was found to be suitable.

The number of generations is a stopping criteria, since it determines the amount of cycles of evolution the genetic algorithm will take. This parameter cannot be neither too small, so that the algorithm will stop prematurely, nor too big, so that the algorithm wastes time going through sub-optimal solutions after having found the optimum. In the examples analyzed in developing this work it has been found that a value of 100 suffices.

The rates of crossover and mutation are complementary in MATLAB. While setting too high crossover rate may lead to local optimum, setting too high mutation rate makes the algorithm to perform randomly, not converging to any solution. The crossover rate of 50% was found adequate for the examples investigated in this work.

### 3.2 Initial Population

An initial population is an important feature for GA.They consist of a set of initial guesses for the solution. If warm guesses are given, the optimization converges faster and to better solutions. For the development of a supporting tool to the detailing three procedures are employed to determine the initial population. They are: randomly creation (MATLAB's default); via a continuous approximation of the original problem; and regarding the eccentricity, which is an incorporation of a practical rule.

For the initial population of continuous approximation, discrete variables, non-differentiable functions are approximated. GA is used to find solutions of global minimum of the continuous problem. To reach the minimum amount of steel the chromosome illustrated in Fig. 3 is used. In Fig. 3 $A$ is the area of each cable, $x_i$ and $y_i$ are the coordinates of the $i$-th cable. Being $i = 1, \ldots, n$ and $n$ is the total possible number of cables. The problem is solved for different $n$, from one to a predefined maximum number of cables. Therefore, for each $n$ it is sought the minimum area the $n$ cables have to have and theirs position, so that the constraints are met.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| A | $x_1$ | $y_1$ | $\ldots$ | $x_i$ | $y_i$ | $\ldots$ | $x_n$ | $y_n$ |

Figure 3. Initial population estimation chromosome of the continuous problem.

The constraints depend on the cable's diameter $\phi$, since coverage and spacing are related to it. This diameter is then approximated through a continuous function. Varying the number of strands in a cable it is possible to correlate cable's area and external diameter [5]. In Fig. 4, the data is shown in blue dots, while the approximation function is shown in solid red line.

In addition, an practical rule of structural concrete design is incorporated. It consists on assuming that the centroid of reinforcement area lies at 10 percent of the cross-section total height from the most tensioned fiber. The initial solution based on this rule is found by calculating the number of strands needed to meet the stress constraint, Eq. (2), then calculating an well-balanced number of cables, and finally setting all cables at the aforementioned $y$-position with zero $x$ coordinate. It is worth mentioning that although this solution is guaranteed to meet the stress constraint, spacing constraints are obviously

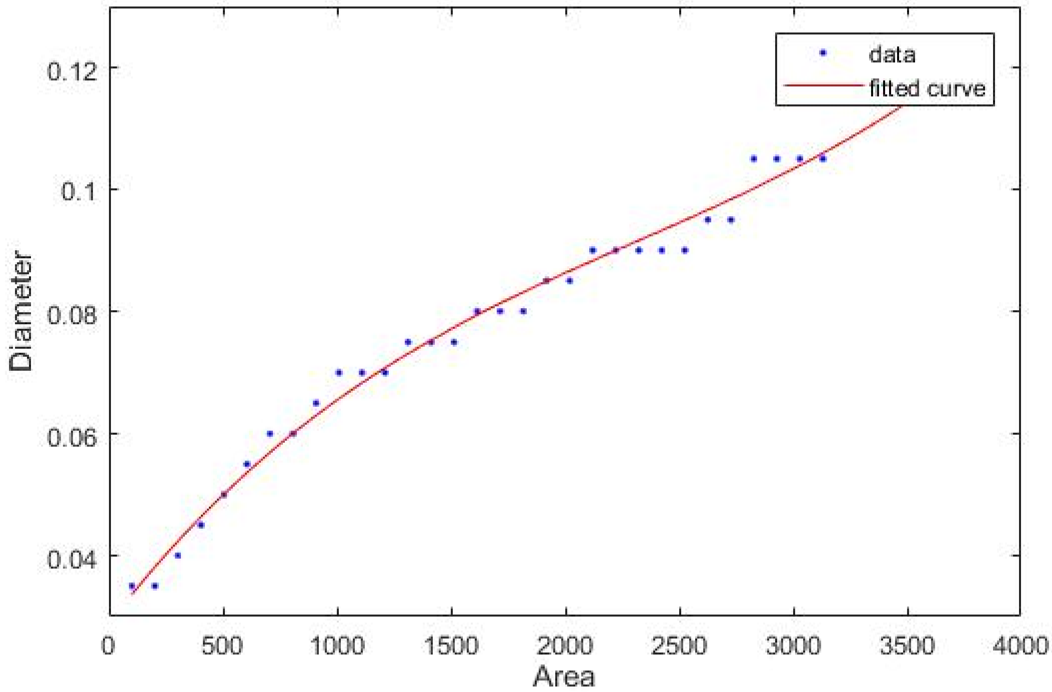


Figure 4. Fitting steel area and cable diameter data.

not met and so are the cover constraints, potentially.

## 4 Objective function

The objective function is the function of optimization that is to be minimized or maximized in a project. In this work the objective function must be directly related to the area of prestressing steel, then the total number of strands in detailing is a good choice of the objective function. That function may be written as

$$F = N \sum_{i=1}^{n} f_i \, , \tag{19}$$

which is the number of strands per cable $N$ multiplied by number of cables in the detailing, calculated by the sum of the active flags $f_i$.

Throughout the development of the work the function has been enhanced to take into account experience and get more practical solutions. In this way, a term is added to bring the cables close to the more tensioned fibers. Since, with the first function, the resulting cables did not have an ideal arrangement. So the function has been changed to

$$F = N \sum_{i=1}^{n} f_i + \sum_{i=1}^{n} f_i (y_i - y_t)^2 \, , \tag{20}$$

in which, $y_t$ is the coordinate of the most tensioned fiber. With additional tests, it could have been seen that this function can be even bettered for practical application. The improvement made regards symmetry of the detailing. Since symmetric detailing are of better execution, the function was changed to

$$F = N \sum_{i=1}^{n} f_i + \sum_{i=1}^{n} (f_i y_i - y_t)^2 + \sum_{i=1}^{n} (x_i)^2 f_i \, . \tag{21}$$

## 5 Results

In this section the carried out tests are presented. The examples concern prestressed beams with posterior adhesion. The Brazilian design codes NBR6118 [6], NBR8681 [7] are employed. They deal with the design of concrete structures, and actions and safety in structures, respectively. Additionally, the prestressing steel adopted was CP190RB12.7, NBR7483 [8] which, according to manufacturer's, has area of one strand $A_{1p} = 101\mathrm{mm}^2$. Moreover, it is used concrete of compressive strength $f_{ck} = 35\mathrm{MPa}$, made of coarse granite aggregate with maximum diameter of $19\mathrm{mm}$ and cement CPV-ARI, NBR16697 [9].

According to Brazilian concrete standard, the cover $c$, considering CAAIII must respect

$$c \geq 45\mathrm{mm}\,, \tag{22}$$

and also,

$$1.2c \geq d_{\max}\,, \tag{23}$$

$$c \geq \frac{\phi}{2}\,, \tag{24}$$

in which, $d_{\max}$ is the maximum diameter of coarse aggregate.

Still according to NBR6118 [6], the horizontal spacing $a_h$ must respect

$$a_h \geq 20\mathrm{mm}\,, \tag{25}$$

$$a_h \geq \phi\,, \tag{26}$$

$$a_h \geq 1.2d_{\max}\,, \tag{27}$$

while the vertical spacing $a_v$ must respect

$$a_v \geq 20\mathrm{mm}\,, \tag{28}$$

$$a_v \geq \phi\,, \tag{29}$$

$$a_v \geq 0.5d_{\max}\,. \tag{30}$$

### 5.1 Girder section

Fig. 5 illustrates the beam considered, whose base cross-section is illustrated in Fig. 6. The detailing was performed for most critical section of the beam. The solution found has two cables of diameter $phi = 9\mathrm{cm}$ with $N = 22$ strands per cable, as depicted in Fig. 7.

From Fig. 7, the coverage encountered is $c = 90\mathrm{mm} - \phi/2 = 45\mathrm{mm}$, which respects

$$c = 45\mathrm{mm} \geq 45\mathrm{mm}\,,$$
$$1.2c = 54\mathrm{mm} \geq d_{\max} = 19\mathrm{mm}\,,$$

and the horizontal spacing $a_h = 183.3\mathrm{mm} - \phi = 93.3\mathrm{mm}$ respects design code limits

$$a_h = 93.3\mathrm{mm} \geq 20\mathrm{mm}\,,$$
$$a_h = 93.3\mathrm{mm} \geq \frac{\phi}{2} = 45\mathrm{mm}\,,$$
$$a_h = 93.3\mathrm{mm} \geq 1.2d_{\max} = 22.8\mathrm{mm}\,.$$

It is yet notorious to say that the tension for this test was also met, since

$$\sigma_{P^c_\infty} = -29253\mathrm{kPa} \leq \overline{\sigma}_c - \sigma_F = -27926\mathrm{kPa}\,,$$

For this it was used an initial population of 250, a set of 100 generations at a crossover rate of 50 percent. It is worth mentioning that the resulting using objective function Eq. (19) the result obtained is shown in Fig. 8, while the result depicted in Fig. 9 is found using objective function Eq. (20).

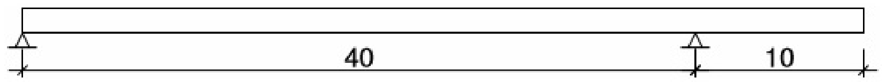


Figure 5. Prestresded beam, presented in meter.

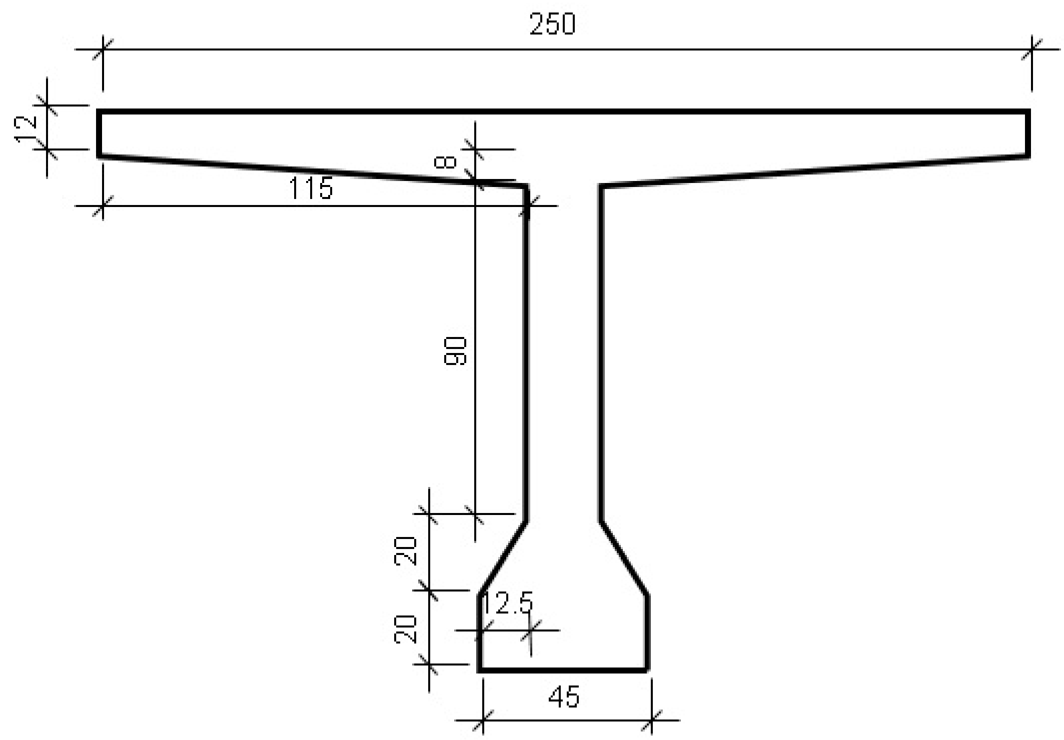


Figure 6. Girder cross-section, presented in centimeter.

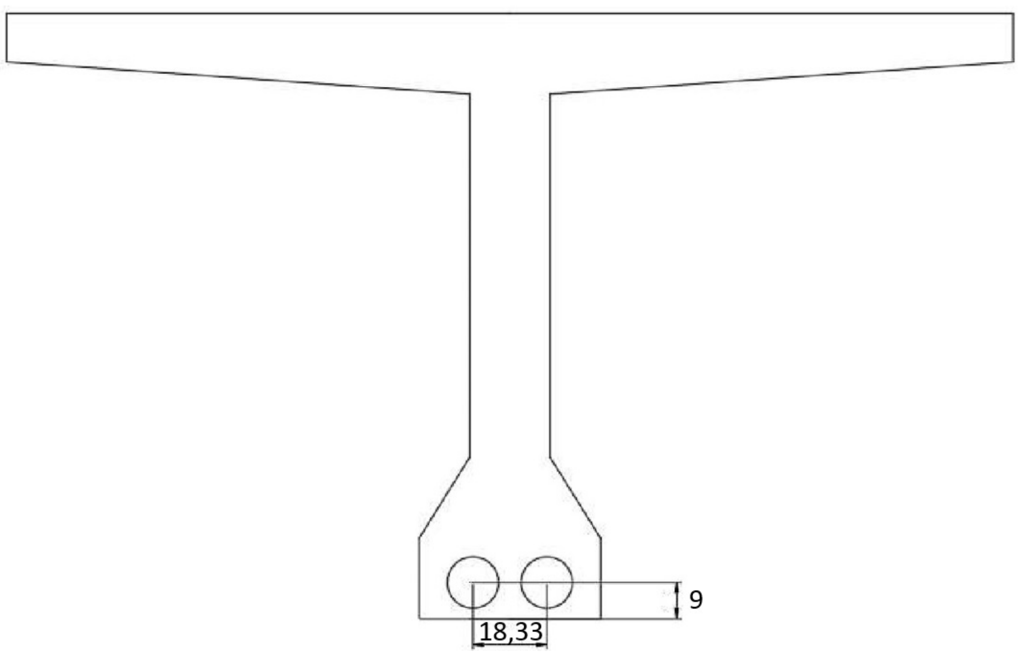


Figure 7. Automated optimum final detailing, presented in centimeter.

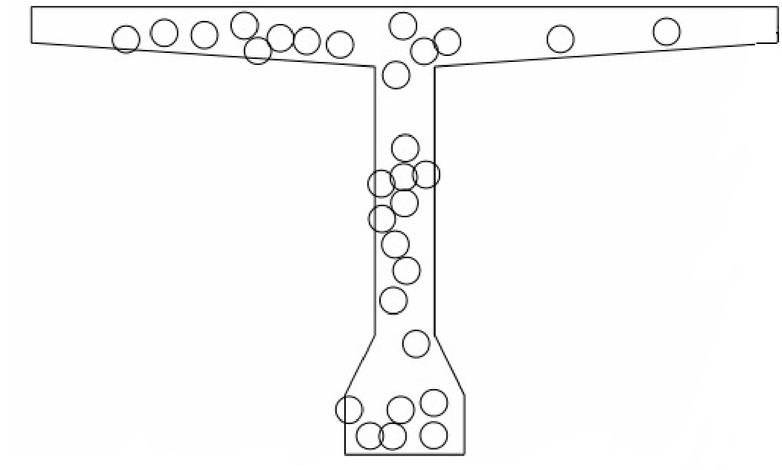

Figure 8. Result for naive objective function.

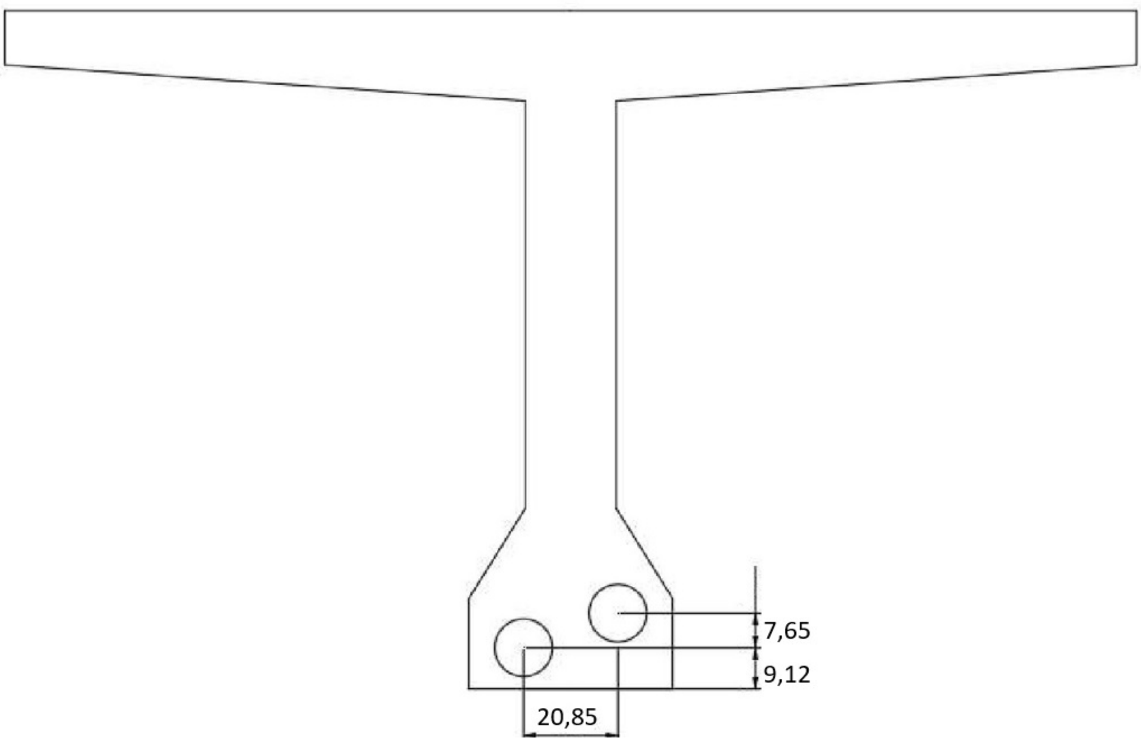


Figure 9. Result for objective function that does not favor symmetry, presented in centimeter.

### 5.2 Box Girder

Considering the cross-section shown in Fig. 10 with a required stress $\sigma_{P^c_\infty} \leq -30711.3\text{kPa}$. The obtained detailing is shown in Fig. 11. It should be noticed that, the concrete adopted here has compressive strength $f_{ck} = 45\text{MPa}$ and the beam geometry differs from Fig. 5, since the spam is $60\text{m}$ and the cantilever part is $20\text{m}$ long.

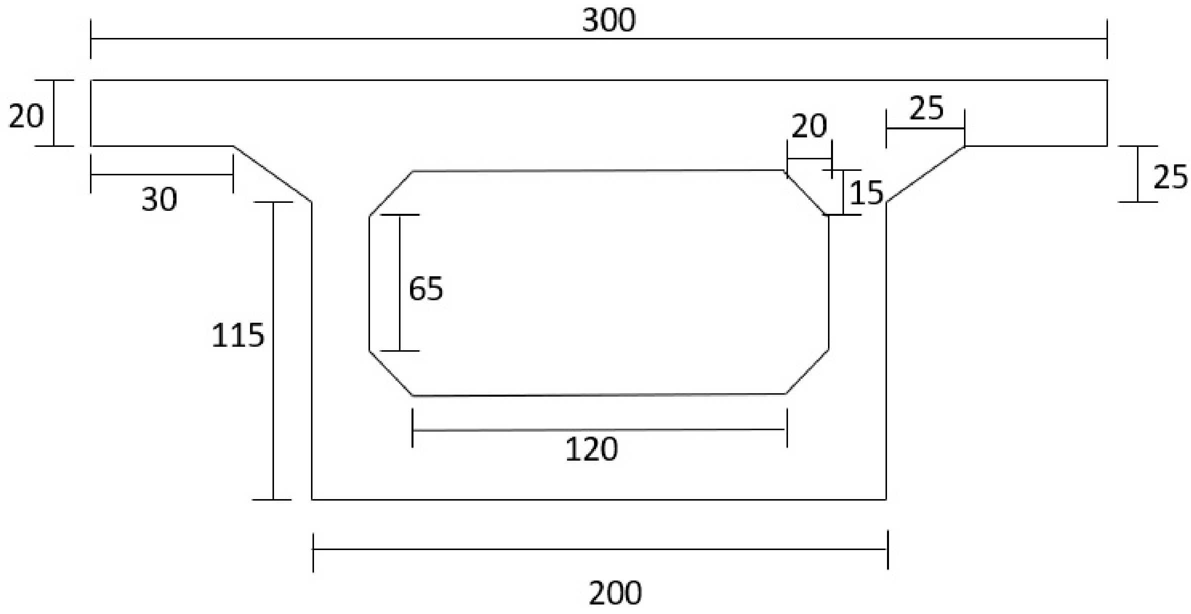


Figure 10. Box girder cross-section, presented in centimeter.

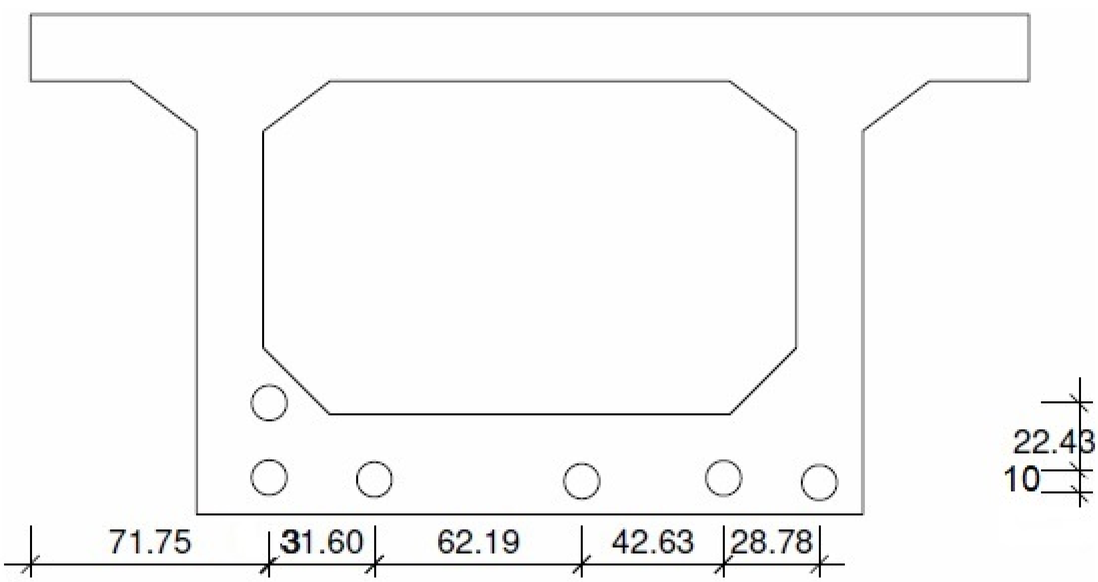


Figure 11. Box girder detailing, presented in centimeter.

As previously seen, the tool solution for that box girder section was not symmetric, which would be more complicated at the time of project execution. However, it can be based on the final solution of the project. The Fig. 12 is a final solution idea based on the solution of the tool, being symmetrical and easier to execute.

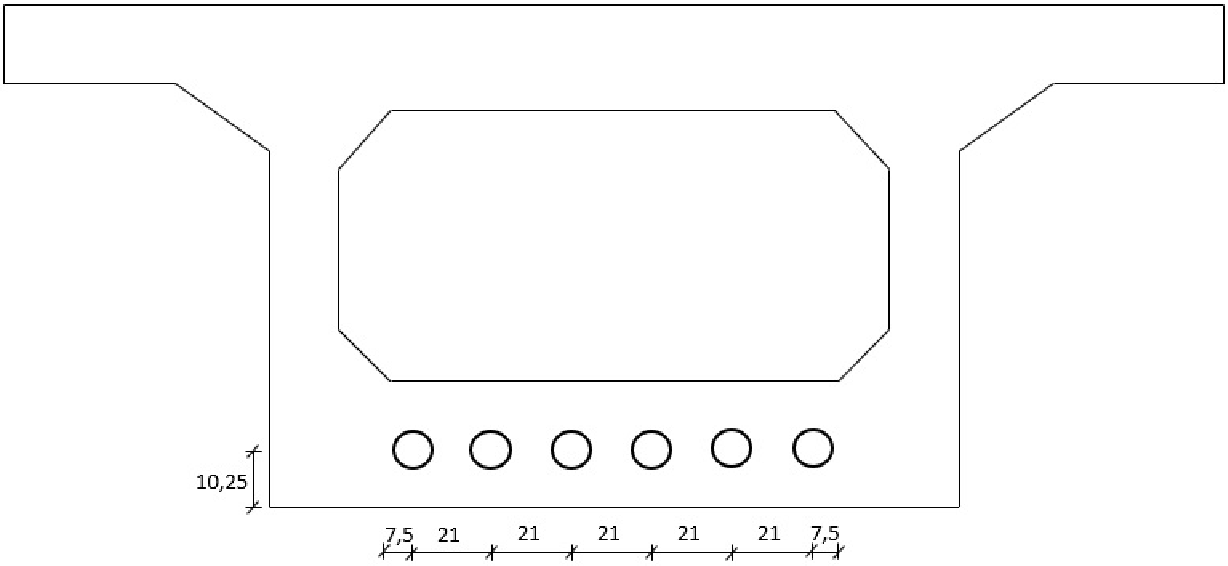


Figure 12. Box girder detailing reset, presented in centimeter.

## 6 Conclusion

In this work a tool was developed to optimize the detailing of the active reinforcement in prestressed concrete beams with posterior adhesion and with complete or limited prestressing. The methodology for the development of this tool was to use the genetic algorithm, with the objective function imposing the minimum volume of steel.

The constructive method of prestressed concrete like any other method requires attention, but due to the fact that it requires an estimation of tension to begin the calculation of the project becomes even more complex. In this way the detailing of armor is fundamental. This step should be performed in the initial phases of a project and can prevent future errors in execution.

The optimum solution that delivers the cross section detailing of the beam was found after some changes in the objective function, as shown in the results. The incorporation of some practical rules did the difference in the search for better solutions, seeking to approximate the cables of the fiber more tensioned and make the same stay symmetrical with respect to $y$-axis. Thus, the solution found is close to the final solution. While the solution in Fig. 7 is very close to the final design, the solution in Fig. 11 is yet to be refined by designer. However, even when the algorithm does not provide a final design, it still furnishes a very good insight of what this design may look like.

The objective function does not imply a project with a more economical solution, however, by reducing the volume of steel, it is understood that this may occur for future projects since the cables are elements significant in the cost final of the project, this because they are high Resistance and high cost.

The tool is a breakthrough in relation to the initial phases of the current projects. The manual process used in today's projects lasts at this stage an average of one day to find a satisfactory solution, based on the estimation of an experienced professional and still does not have the assurance that the solution found is the best possible. The tool developed in this project finds an optimized response in minutes, and can help new designers, innovate section models, reduce rework and execution time. For future projects The tool will be useful not to get a final project response, but it is of great value to apply it as an indicator of where it is most promising to detail the armor.

## Acknowledgements

The authors would like to thank Ibmec for supporting this research project.

## References

[1] Cholfe, L. & Bonilha, L., 2017. *Concreto Protendido*. PINI, São Paulo.

[2] Hughes, J. F., Van Dam, A., Mcguire, M., Sklar, D. F., Foley, J. D., Feiner, S. K., & Akeley, K., 2013. *Computer Graphics Principles and Pactice*. Pearson Education, Ohio, USA.

[3] Carvalho, R. C., 2017. *Estruturas em Concreto Protendido*. PINI, São Paulo.

[4] de Leon F. de Carvalho, A. P., 2009. *Algoritmos Genéticos*. São Carlos.

[5] Protende, 2013. *Catálogo, Sistemas e Métodos*. http://protende.engenharia.ws/CAT

[6] NBR6118, 2014. *Projeto de estruturas de concreto - Procedimento*. Associação Brasileira de Normas Técnicas, Rio de Janeiro.

[7] NBR8681, 2003. *Ações e segurança nas estruturas - Procedimento*. Associação Brasileira de Normas Técnicas, Rio de Janeiro.

[8] NBR7483, 2008. *Cordoalhas de aço para estruturas de concreto protendido - Especificação*. Associação Brasileira de Normas Técnicas, Rio de Janeiro.

[9] NBR16697, 2018. *Cimento Portland - Requisitos*. Associação Brasileira de Normas Técnicas, Rio de Janeiro.