Optimization of the Design of Structures in Coverage Using the Genetic Algorithm Method

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Abstract: In this research work, an optimization of the design of steel structures is developed through Genetic Algorithms (Gas) with the objective of reducing the amount of material and with them the cost, for which the programming of the GAs tool in the Fortran programming language with the SAP2000 Application Programming Interface (API) v.19 using Visual Studio Professional 2015—Intel® Visual Fortran with Parallel Studio XE. The GAs method consists of randomly searching the Objective Function (OF) of the optimal variables with restrictions. The OF defined by the weight of the structure, the variables in relation to the cross sections of the structural elements and the constraints are the design of resistance using the method of Load and Resistance Factor Design (LRFD), restriction of displacements and restriction of the ratio of slenderness considered in the National Building Regulations (RNE), whose GAs search parameters are given by probability of crossing 70% by simple crossing strategy, probability of mutation 20%, elitism of 5% and maximum number of generations according to the profile. The examined metal structure is a cover with five double-body warren arches with 32 m light connected with 24 joists both with welded connections, that is, rigid. The metal structure was evaluated on demand for loads (dead load, live load, snow load, wind load and earthquake loads). The structural design was carried out with the following profiles: circular, tubular, square, angular and Normal Profile with I-shaped section (IPN) of which the most optimal was the tubular profile. The outer diameters of the cross section are: diagonal with a diameter of 1 in, lower flange with a diameter of 2 3/8 in, upper flange with a diameter of 1 1/2 in, inner belt with a diameter of 1 in and belt. outside with a diameter of 1 1/2 in.

Key words: GA, structure optimization, resistance design with artificial intelligence, design by resistance, bending buckling.

1. Introduction

Currently in the design of steel structures, the trial-error process is still preserved, that is, the simulation process is still preserved and not the design process. The design process consists of finding the variable (type of profile and its section of the elements of the metal structure for coverage) it meets the design restrictions. When there are many elements in a structure, the simulation process generally takes a lot of time or complexity to find the design elements, however, using artificial intelligence techniques such as GAs, it is easy, straightforward and optimal results are obtained.

This research work is motivated because currently in the world the construction sector is in constant development where the shortage of raw material and demand for building materials motivate to reduce the amount of material.

In the first part of the research work, it contemplates the theory on the design of resistance of the elements subjected to different types of load and combinations by the method of LRFD and the relevant factors involved in design as the slenderness relationship as well the GAs itself contemplate a brief description of the basic operators, optimization flowchart of the steel structure, function definition objective and restrictions such as resistance, displacement and geometric.

Finally, after executing the GAs technique for all the proposed profiles, efficient results were obtained

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and in this way the objectives set out in this research work are fulfilled, likewise, the results are shown in graphs and tables depending on the restrictions from the first generations to the last generations, also observing the convergence of the optimal variables.

1.1 Problem Statement

The construction sector is in constant development where the shortage of raw materials and the increase in demand for material motivate to reduce the amount of material in the structures without compromising its security, and with that they try conserving natural resources and aim at decreasing the materials used in the structures of construction, as well decreasing the amount of material also affects other aspects, such as the transport and assembly, and with it the consumption of fuels and non-renewable energy.

2. Material and Methods

2.1 Structural Analysis—Finite Element Method

A general formulation of the method of the finite elements for structure analysis, to start it is necessary to divide the entire domain of model under analysis, with elements for which they are known its interpolation functions, this procedure it is known in specialized books as element technology [1].

2.1.1 Stiffness Matrix

The stiffness matrix is obtained by developing an element of “ n ” nodes, the displacement vector for an item is conveniently ordered in the equation and the function vector equation form is:

$$N = \left(\begin{bmatrix} N_1 & 0 \\ 0 & N_1 \end{bmatrix} \begin{bmatrix} N_2 & 0 \\ 0 & N_2 \end{bmatrix} \dots \begin{bmatrix} N_n & 0 \\ 0 & N_n \end{bmatrix} \right)$$

$$q = \begin{pmatrix} \begin{bmatrix} v_1 \\ w_1 \end{bmatrix} \\ \begin{bmatrix} v_2 \\ w_2 \end{bmatrix} \\ \vdots \\ \begin{bmatrix} v_n \\ w_n \end{bmatrix} \end{pmatrix}$$

Unitary deformation matrix displacement is:

$$B = \left(\begin{bmatrix} \frac{\partial N_1}{\partial r} & 0 \\ 0 & \frac{\partial N_1}{\partial z} \\ \frac{\partial N_1}{\partial z} & \frac{\partial N_1}{\partial r} \\ \frac{N_1}{r} & 0 \end{bmatrix} \begin{bmatrix} \frac{\partial N_2}{\partial r} & 0 \\ 0 & \frac{\partial N_2}{\partial z} \\ \frac{\partial N_2}{\partial z} & \frac{\partial N_2}{\partial r} \\ \frac{N_2}{r} & 0 \end{bmatrix} \dots \begin{bmatrix} \frac{\partial N_n}{\partial r} & 0 \\ 0 & \frac{\partial N_n}{\partial z} \\ \frac{\partial N_n}{\partial z} & \frac{\partial N_n}{\partial r} \\ \frac{N_n}{r} & 0 \end{bmatrix} \right)$$

The deformations are given by $\epsilon = Bq$, the stiffness matrix in the standardized system for an axial symmetry structure is given by the equation, to obtain the expressions of the loads, which is proceeded in a similar way.

$$k = t \int_{-1}^1 \int_{-1}^1 (B^T)(D)(Br)(J)(d\epsilon)(dn) \quad (1)$$

where:

t : represents the angle of revolution that rotates every finite element in the plane of the characteristic section of discretized revolution.

B : Matrix strain unit displacement or simply deformation matrix unitary equation.

D : Element property matrix.

r : Radial coordinate for each point of the element finite equation.

J : Jacobian matrix.

2.2 Design Strength of Steel according to National Building Regulations (RNE)

The RNE considers the following aspects for the design of steel strength.

2.2.1 Standard E.090 of Metallic Structures

The RNE of Perú [2] considers the LRFD method for the design of metallic structures by resistance considering the philosophy of load considerations combined.

2.2.2 Limit Slenderness Relations (LSR)

For elements whose design is based on forces of compression, slenderness ratios (KL/r) should not preferably exceed 200. For items whose design is based on tensile forces, relationships of slenderness (KL/r) should not preferably exceed 300 [2].

2.2.3 Tensile Strength Design

The design resistance of elements according to the LRFD tensile method P_n must be lower value obtained according to the creep limit states in the total area of breakage in the net area [2].

$$\phi_t = 0.90$$

$$P_n = F_y A_g \quad (2)$$

$$\phi_t = 0.75$$

$$P_n = F_u A_e \quad (3)$$

where:

A_e = Net effective area.

A_g = Total area of the element.

F_y = Minimum creep stress specified.

F_u = Minimum tensile strength specified.

P_n = Nominal axial resistance.

2.2.4 Resistance Design in Compression Elements for Buckling

There are three general modes according to which axially loaded elements can fail. These are: flexing buckling, local buckling and twisting buckling. These buckling modes are briefly defined as follows [2]:

Flexing buckling, also called buckling of Euler, is the primary type of buckling analyzed. Members are under flexion when they become unstable.

Local buckling occurs when some parts or parts of the cross section of a column are so thin

Flexing twisting buckling may occur in columns that have certain configurations in their cross section.

The longer a column is for the same cross section, the greater its tendency to buckle and the lower the load it can bear.

2.2.5 Euler's Formula

For a column to buck elastically, it must be long and slender. Your buckling load P can be calculated with the following Euler's formula [3]:

$$P = \frac{\pi^2 EI}{L^2} \quad (4)$$

This formula is usually written in a slightly different way that implies the slenderness relationship of the column. It is known $r = \sqrt{\frac{I}{A}}$, then $I = Ar^2$. Substituting this value in Euler's formula, and dividing both sides by the cross-sectional area, you get the buckling effort from Euler's formula:

$$\frac{P}{A} = \frac{\pi^2 E}{(L/r)^2} = F_e \quad (5)$$

2.3 End Restrictions and Effective Element Length

The restriction on the extremes and its effect on ability to load a column is really a very important concept. The columns with restrictions of appreciable rotation and displacement can withstand loads much greater than those with little end rotation restriction, as is the case of columns with articulated ends. The factors of the effective length can be seen in Fig. 1 according to the type of connection at its ends.

Approximate values of the effective length factor K					
The blue lines show the buckling shape of the column	(a)	(b)	(c)	(d)	(e)
theoretical k values	0.5	0.7	1.0	1.0	2.0
Recommended design values when actual conditions are approximate	0.65	0.80	1.2	1.0	2.10
symbols for extreme conditions		Rotation and translation impeded.			
		Rotation free and transfer impeded.			
		Rotation hindered and free transfer.			
		Rotation and free transfer.			

Fig. 1 Effective length factors according to McCormac [4].

2.4 Resistance Design in Compression Elements for Flexing Buckling

According to LRFD [5], the strength of compression element design can be determined as Eq. (6):

$$\begin{aligned} P_n &= F_{cr} A_g \\ \phi P_n &= \phi F_{cr} A_g \\ \phi_t &= 0.90 \end{aligned} \quad (6)$$

The Eqs. (7, 8) show how you can determine F_{cr} , the bending buckling effort of a column, for members without slender elements:

$$\begin{aligned} \frac{KL}{r} &\leq 4.71 \sqrt{\frac{E}{F_y}} \vee \frac{F_y}{F_e} \leq 2.25 \\ F_{cr} &= \left[0.658^{\frac{F_y}{F_e}} \right] F_y \end{aligned} \quad (7)$$

$$\begin{aligned} \frac{KL}{r} &> 4.71 \sqrt{\frac{E}{F_y}} \vee \frac{F_y}{F_e} > 2.25 \\ F_{cr} &= 0.877 F_e \end{aligned} \quad (8)$$

In these expressions, faith is the buckling effort elastic critic, that is, Euler's effort—calculated with the Effective Length (KL) of column of the Eq. (5).

2.5 Cut Resistance Design

According to LRFD [5], in general, the shear is not a problem in the steel beams because the souls of the rolled profiles are able to withstand large cutting forces. A series of common situations are indicated below where the shear could be excessive.

If large concentrated loads are placed nearby from the supports of a beam, they will originate large internal forces without corresponding increases in the bending moments.

Probably the most common shear problem occurs when two structural members (like a beam and a column) are rigidly connected to each other, so that their souls are in the same plane. This situation occurs frequently at the junction of beams (or stringers) and columns in rigid frame structures.

The design cut resistances for stiffened and non-stiffened souls are $\phi_v V_n$. where:

$$\phi_v = 0.90$$

V_n = Nominal cut resistance defined as Eqs.(9-11):.

$$\begin{aligned} \text{Para } h/t_w &\leq 1,098/\sqrt{F_{yw}} \\ V_n &= 0.60 F_{yw} A_w \end{aligned} \quad (9)$$

$$\begin{aligned} \text{Para } 1,098/\sqrt{F_{yw}} &< h/t_w \leq 1373/\sqrt{F_{yw}} \\ V_n &= 0.60 F_{yw} A_w \left(\frac{1,098/\sqrt{F_{yw}}}{h/t_w} \right) \end{aligned} \quad (10)$$

$$\begin{aligned} \text{Para } 1,373/\sqrt{F_{yw}} &< h/t_w \leq 260 \\ V_n &= A_w \left(\frac{910,000}{(h/t_w)^2} \right) \end{aligned} \quad (11)$$

2.6 Permissible Deformations according to American Association of State Highway and Transportation Officials (AASHTO) 2010

According to McCormac [4], deflections of steel beams generally are limited to certain maximum values. Some good reasons to limit deflections are as follows:

Excessive deflections can damage the materials joined or supported by the considered beam. The cracks in the soffits caused by large deflections in the stringers that support them are an example.

The appearance of the structures is affected by excessive deflections.

Excessive deformations do not inspire confidence in people who use a structure, although there is complete security from the point of view of resistance.

It may be necessary that different beams that support the same load have the same deflections.

For cases where delicate and precision machinery is supported, maximum deflections may be limited to 1/1,500 or 1/2,000 of the length of the clearing. The AASHTO 2010 Specifications set the deflections of the steel beams and beams due to live loads and impact at 1/800 of the clearing (for bridges in urban areas that are also used by pedestrians, the AASHTO Specifications recommend a maximum value of 1/1,000 of the length of the clearing).

2.7 Steel Structure Profiles

The sections of the profiles are standardized and standardized by the American Society for Testing and Materials.

2.7.1 ASTM Standard for Steels

According to American Society of Civil Engineers (ASCE) [6], the ASTM standard is the most used internationally to designate and regulate the quality of steels' construction that are commercially offered as products finished such as construction bars corrugated and smooth, structural profiles, commercial profiles, plate and foil. The standard basically guarantees the minimum mechanical properties and weldability of steels, since the use of these is oriented to the construction and various metal structures of industry (riveted, welded or bolted). The standards published by ASTM issue designations fixed systems for each type of steel with its respective specifications and requirements to be used by manufacturers and users of steels.

2.8 Genetic Algorithms

According to Michalewicz [7], he says that GAs are adaptive methods that can be used to solve search problems and optimization which are based on the genetic process of living organisms. Throughout the generations, populations evolve in the nature of chord with the principles of natural selection and survival of the strongest, nominated by Darwin (1859). By imitation of this process, the GAs are able to create solutions for real world problems [8]. Its basic operators are [9]:

Initialization: The initial population of candidates is randomly generated in the search space.

Evaluation: Once the population started or a descendant population, fitness values of the candidate solutions are evaluated.

Selection: The general idea of this step is preference of the best solutions than the worst, making use of selection procedures, such as roulette selection, elite selection, selection climbing, tournament selection.

Recombination: The procedure combines parts of two or more apparent solutions to create new solutions, possibly better.

Mutation: While recombination operates with 2 or more parental chromosomes, the mutation locally, but randomly modifies a solution.

Replacement: The descendant population created by selection, recombination and mutation replace to the originally created population. Various replacement techniques exist in GAs as the elitist replacement, by steady state or proportional to fitness.

The Fig. 2 shows the flowchart of the cyclic process of the genetic algorithms and the sequence that must be followed for their basic operators already described.

2.9 Formulation of the Optimization Problem of the Steel Structure in Coverage

The Fig. 3 describes the flowchart of the main algorithm used to solve the problem of the optimization design of metallic structures in coverages by means of genetic algorithms, that is, taking into account the previous flowchart. Whose steps and cycles are part of the structure of the program carried out.

Fig. 2 Flowchart of Genetic Algorithms Method.

Fig. 3 Flowchart for the optimization of the design of the metallic structure in coverage by means of Genetic Algorithms.

2.9.1 Objective Function Approach

The problem of optimization of measures is to find optimal cross sections, or dimensions, of elements of a stable and safe structural system whose topology and shape are fixed, the function objective is related to the weight or volume of the amount of material.

The main objective in this optimization problem is to minimize the cross sections, so from them the independent variables of the OF would become the areas of the cross sections since they will be evaluated in each generation.

Therefore, the OF will be defined as:

$$\text{Minimize } F_1 = \sum_{i=1}^n (W_i(A_i, L_i)) \quad (12)$$

The restrictions of the OF:

$$\sigma_{max} \geq \sigma_i$$

$$\delta_{max} \geq \delta_i$$

$$LSR \geq L/r$$

where:

F_1 = OF (weight).

A_1 = Areas of the cross sections of the elements structural.

L_1 = Length of the structural elements.

σ_{max} = Maximum allowable resistance effort.

δ_{max} = Maximum allowable resistance deformation.

r = Turning radius.

2.9.2 Resistance Restrictions

If the element is in compression:

$$F_e = \frac{\pi^2 E}{(L/r)^2}$$

If he meets $2.25 \geq F_y/F_e$ then the effort

critical will be calculated $F_{cr} = \left[0.658^{\frac{F_y}{F_e}} \right] F_y$

otherwise it will be $F_{cr} = 0.877 F_e$.

Further:

$$\sigma_{combined} = \sigma_{flector} + \sigma_{axial load}$$

If $F_{cr} > abs(\sigma_{combined})$ then it will comply with resistance restriction (LRFD method) otherwise the objective function will be penalized.

If the element is in tension:

$$F_{tension} = 0.9 F_y$$

$$\sigma_{combined} = \sigma_{flector} + \sigma_{axial load}$$

If $F_{tension} > abs(\sigma_{combined})$ then it will comply with the resistance restriction (LRFD method) otherwise the objective function will be penalized.

The nominal shear resistance of a soul without stiffening or stiffening is specified as:

$$V_n = 0.6 F_y A_w C_v$$

where F_y is the minimum creep resistance of the steel, A_w is soul area and C_v will depend on the geometric

and mechanical properties.

2.9.3 Deflection Restriction

The specifications AASHTO 2010, fix the deflections of the beams and traves of steel due to live loads and impact on 1/800 of the clearing (32 m) [4].

$$0.04 \text{ m} \geq \delta_i$$

2.9.4 Geometric Restrictions

To limit the relationship of slenderness for economic reasons you have [2]:

For compression elements:

$$200 \geq L/r$$

For tension elements:

$$300 \geq L/r$$

3. Results

The examined metal structure is a cover with 5 arched beams (with a height of 5.42 m). Type double body warren was connected with 24 joists both with welded connections, that is, rigid as shown in Fig. 2.

The beam is consisting of 408 diagonals (0.44 and 0.50 m near the ends and 0.50 m in the middle), 201 flanges lower (0.25 m near the ends and 0.45 m in the intermediate) and 204 upper flanges (0.25 m near the extremes and 0.50 m in the middle) as shown in Fig. 3, which are the variables of the OF.

The optimization will be developed on a geometrically and topologically defined structure and assign the dead load, live load, snow load, wind load and earthquake load established in the program SAP2000 v.19 [10], all of which will receive the different internal charges; such as axial loads, bending moments (the connections of the elements are rigid) and shear forces; prior execution, so that these are evaluated by GAs. According to the defined restrictions and determination of their OF (penalty conditioner that is multiplied to OF by the number of elements that violate restrictions $\times 10^5$) in the programming language Fortran 95, the population (main list) is defined by individuals, represented by lists containing the commercial sections of the variables of the OF (5 variables named for the AGs genes), as well another list is created that

contains the score of each individual according to the OF, where these individuals, once the program is initialized, will go through a random search process, after assigning the scores to each individual, by the basic operators. Selection of suitable individuals with an elitism of 5 of the which parents (2 pairs) of high score will be selected to make the crossing and generate two descendants and according to the probability assigned to be mutated, then the rating of these descendants is assigned to pass to the reduction or replacement operator where the convenience of these descendants will be evaluated to integrate the population, that is to say if they have good qualifications they will replace two other individuals less fit.

Fig. 4 shows the convergence history during the execution of the program for the different profiles, according to the diagram the most optimal is the tubular profile. An exception is made for the square profile since it does not meet the demands of loads for its commercial sections.

Table 1 details the optimal variables of the OF for each profile.

3.1 Optimization of the Steel Structure for a Tubular Section through GAs

Table 2 shows the commercial bars for the tubular section and its geometric properties, all these represent

Fig. 4 Structure evaluated.

Fig. 5 Function variables objective.

Fig. 6 Convergence diagram at minimum weight for profiles.

Table 1 Optimal variables.

Design variable	Circular (")	Tubular (")	Square (mm)	Angular (mm)	IPN (mm)
Diagonal	3/4	1	18	40	80
Lower flange	1	2 3/8	24.5	40	100
Upper flange	1	1 1/2	18	40	80
Inner element	3/8	1	11	40	100
Outer element	7/8	1 1/2	24.5	40	180
Weight (kg)	14,418.91	11,429.10	Penalized	15,833.69	41,522.90

the domain of the OF ranging from 1/2" and 2 1/2", from these known variables a dynamic random population will be formed consisting of individuals

whose genes are the diameters outside the tubular section, the individual will be represented by a list formed by the values of the outer diameters (genes).

Table 2 Design variables for the tubular section.

Tubular section			
External diameter (")	Thickness (mm)	Area (cm ²)	Inertia (cm ⁴)
1/2	1.50	0.53	0.08
5/8	1.50	0.68	0.18
3/4	1.50	0.83	0.34
7/8	1.50	0.98	0.47
1	1.50	1.13	0.64
1 1/4	1.50	1.63	1.03
1 1/2	1.50	2.89	1.52
1 3/4	1.50	4.67	2.10
1 7/8	1.50	5.79	2.43
2	1.50	7.06	2.78
2 3/8	1.50	12.00	3.98
2 1/2	1.50	14.05	4.42

(a) Generation 1 individual 2

(b) Generation 15 individual 2.

(c) Generation 35 individual 7

(d) Generation 45 individual 11

Fig. 7 Results of the application of GAs for different generations and individuals.

The research parameters of the GAs are: crossing probability 70% by simple crossing strategy, 20% mutation probability, elitism of 5, maximum number of generations 45 and number of individuals 80.

The Figs. 7.a, 7.b, 7.c and 7.d the state of resistance of the different elements that make up the warren beam of 32 meters of light and those that present the greatest requests for loads (center beams) for the best

individual of the indicated generations. Where colors are defined by a value (ratio) that is the relationship between demand effort and resistance effort, then elements that have values greater than 1 are overstressed and values less than 1 will behave according to the constraints. It is observed that from the first generation it complies with the 3 restrictions defined, due to the number of individuals assigned.

The Fig. 7a represents the best individual for the generation 1, the Fig. 7b represents the best individual for the generation 15, the following Fig. 7c represents the best individual for the generation 35 and the figure 7.d represents the best optimal individual for IPN in the last generation (45).

4. Conclusion

The metallic structure in coverage was defined geometrically in the Sap2000 v.19 program, the same that was implemented with the GAs optimization method, written in the Fortran programming language, supported by the API Sap2000 v.19, whose parameters of the search for the GAs method was a 70%, crossover probability by simple crossover strategy, 20% mutation probability, elitism of 5%, maximum number of generations 45 and number of individuals 80, likewise whose assigned restrictions were resistance restriction through the methodology of the LRFD, restriction of the displacements of the nodes of the structure less than 0.04 m. and the geometric restriction of the elements depending on the slenderness ratio according to the RNE-Peru.

The method of the GAs, performs an automatic and optimal design for the steel structure of the arc type warren beam of a free length of 32 m., Under the parameters established according to the RNE-Peruvian Standard and under the load request, where the optimal profile was the tubular profile whose outer diameters of its elements are: diagonal with a diameter of 1 in, lower flange with a diameter of 2 3/8 in, upper flange with a diameter of 1 1/2 in, inner belt with a diameter of 1 in and belt. outside with a diameter of 1 1/2 in.

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