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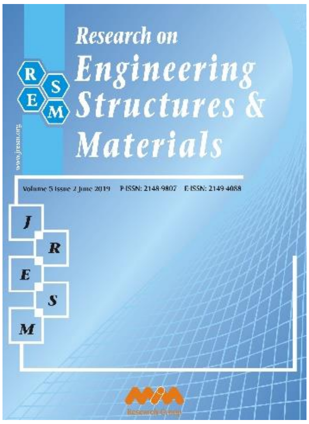

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Research Article

Verification of a genetic algorithm for the optimization of stiffened plates through the constructal design method

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Abstract

This work is a feasibility study of a Genetic Algorithm (GA) based geometric optimization of stiffened plates subjected to transverse loads. For that, the Constructal Design method was used in order to define the search space, aiming to minimize the stiffened plate's central deflection, while keeping the total volume of material constant. The number of longitudinal Nls and transverse Nts stiffeners and the relation hs/ts, the ratio between the height and the thickness of the ribs, were considered as degrees of freedom of the studied optimization problem. In order to estimate the displacement field of the plate reinforced with stiffeners, the Finite Element Method (FEM) was used through the ANSYS® Mechanical APDL software. For the verification, the results obtained in the present study were compared with those obtained by Troina (2017), which used Exhaustive Search (ES) as optimization technique. The results indicated that is more efficient using GA than ES since the former requires the analysis of a lesser amount of cases in order to determine the optimal geometric configuration; there being reductions of up to 47,09% on the number of simulations.

1. Introduction

Thin plates reinforced with stiffeners are broadly employed to resist transverse distributed and/or concentrated loads in a wide gamma of structures such as bridges, ship hulls, vehicles and ships [1]. According to [2], the foremost advantage of using stiffened plates is on the structural efficiency because these structures allow to reduce the total weight without compromising on its rigidity.

Stiffened plates were the subject of study of many researches, among them we can highlight: Bedair [3] studied these structural elements, idealizing them as plate-beam system, through the Sequential Quadratic Programming (SQP) method; Kallassy and Marcelin [4] investigated the feasibility of applying Genetic Algorithms (GA) on the topological optimization of the reinforcements in stiffened plates; the Boundary Element Method (BEM) was used by Tanaka and Bercin [5] to evaluate the influence of stiffeners with various cross-sections on the mechanical behavior of plates under bending; Sapountzakis and Katsikadelis [6] employed the Analogous Equation method to analyze beam-reinforced plates in order to estimate the shear stress on the interface between plate and stiffeners. For that, simply supported rectangular plates with one longitudinal reinforcement with different heights were considered: Hasan [7] investigated the optimal positioning of rectangular beam-type reinforcements on stiffened plates subjected to a

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static and uniform load by using the *NASTRAN®* software to determine the displacements and maximum stresses acting on the plate; Troina [8], through the Constructal Design method associated with Exhaustive Search (ES), performed a study with respect to the central deflection of rectangular stiffened thin plates minimization.

Although it enables the individual evaluation of each degree of freedom involved in the studied optimization problem, the usage of ES in the search space defined by the application of the Constructal Design method is computationally expensive when a broad number of degrees of freedom are studied. Therefore, GA becomes an interesting alternative for the proposed geometrical optimization process.

Thus, this study seeks to evaluate the feasibility of applying GA, associated with computational modeling and the Constructal Design method, to determine the optimal geometric configuration that minimizes the central deflection of stiffened plates. For that, the verification was performed through a comparison between the obtained results and those presented by Troina [8].

2. Constructal Design Method

The Constructal Theory presumes that geometrical configuration of a flow system is not result of chance, but actually it is the result of a physical principle called Constructal Law, being, thus, a physics phenomenon. These systems evolve in such a way that it better distributes the flaws, easing the flow. More specifically, when it comes to Solid Mechanics problems, the flow is related to the flow of stresses acting on the structural component [9].

According to Bejan [10], the Constructal law is employed through the Constructal Design method, which enables determining the best configuration of a given system. For that, the flow should be malleable and the geometry should be subjected to global restrictions, besides varying the degrees of freedom.

In the present work, the Constructal Design method was employed seeking to define the search space for the GA-based optimization. For that, a plate with length a = 2 m, width b = 1 m and thickness t = 0.02 m was picked as reference. Then, a volume fraction ϕ (as Eq. (1)) of the reference plate was transformed into transverse and longitudinal stiffeners.

$$\phi = \frac{V_s}{V_r} = \frac{N_{ls}(ah_s t_s) + N_{ts}[(b - N_{ls} t_s)h_s t_s]}{abt} \tag{1}$$

being, V_r the volume of the reference plate and V_s the volume of the plate that was transformed into longitudinal and transverse reinforcements, i.e., the stiffeners volume. Moreover, N_{ls} and N_{ts} stand for, respectively, the number of stiffeners in the longitudinal and transverse directions. Lastly, h_s and t_s are the height and thickness of the stiffeners, respectively. Figure 1 shows schematically a plate with 2 longitudinal reinforcements and 3 in the transverse direction. It is worth highlighting that the dimensions a and b were kept constant in relation to the reference plate in the stiffened plates, thus the volume converted into stiffeners was taken from the reference plate by reducing its thickness.

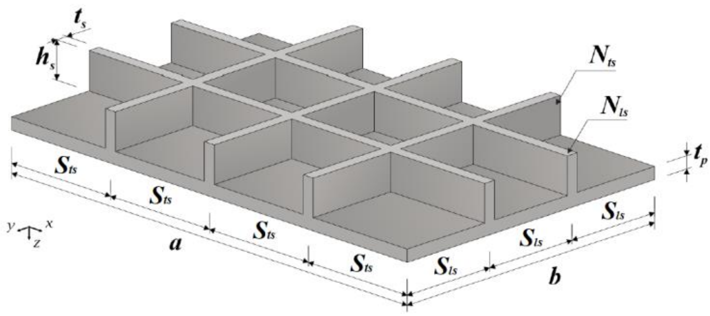

Fig. 1 Stiffened plate with 2 longitudinal and 3 transverse stiffeners

Aiming to determine the geometric configuration that optimizes the mechanical behavior of stiffened plates with respect to the central deflection, the following degrees of freedom were considered: N_{ls}, N_{ts} and h_s/t_s (ratio between the stiffeners' height and thickness). As in [8], 25 different combinations of transverse and longitudinal stiffeners, varying N_{ls} and N_{ts} from 2 to 6, were analyzed. Furthermore, t_s values were adopted based on standard thickness of steel plates between 3.75 mm and 76.6 mm. In addition, h_s should not be higher than 0.3 m in order to avoid a disproportionality between the height of the longitudinal and transverse directions reinforcements and the planar dimensions of the plate. It is important to highlight that the stiffeners have a rectangular cross section and are evenly spaced as shown, respectively, in Eq. 2 and 3:

$$S_{ls} = \frac{b}{(N_{ls}+1)} \tag{2}$$

$$S_{ts} = \frac{a}{(N_{ts}+1)} \tag{3}$$

Lastly, as in [8], 5 volume fractions ϕ: 0.1, 0.2, 0.3, 0.4 and 0.5 were studied. Regarding the material of the simulated plates, structural steel A-36 with Poisson coefficient and Young's modulus of, respectively, 0.3 and 200 GPa was considered. All the numerically simulated stiffened plates were considered as simply supported and subjected to a uniform transverse load of 10 kPa.

3. Genetic Algorithm

Darwin, on his theory of evolution by natural selection, explained how biological organisms evolve through generations based on the principle of survival of the fittest. Since such a mechanism works in nature, simulating the natural evolution through a method that deals with optimization problems becomes an interesting alternative [11]. Thus, GA is a meta heuristic optimization method based on nature, using natural evolution and genetics concepts, where operators such as selection, reproduction and mutation are applied [12].

The GA was implemented in JAVA and integrated with ANSYS® by utilizing scripts in APDL (Ansys Parametric Design Language). The implemented algorithm can be visualized, schematically, in Fig. 2. The process starts with a population constituted of random individuals and then, through ANSYS® *Mechanical* APDL software, the mechanical behavior of each individual is estimated. Thereafter, based on the obtained deflection results, each individual is availed and ranked. Then, a new population is created by combining desirable characteristics from the current generation through the selection, reproduction and mutation genetic operators. Lastly, the current population of individuals is replaced by the newly generated offspring, excepting the fittest individuals, which are preserved unchanged through the elitism strategy. This process is repeated until the stop criteria is satisfied.

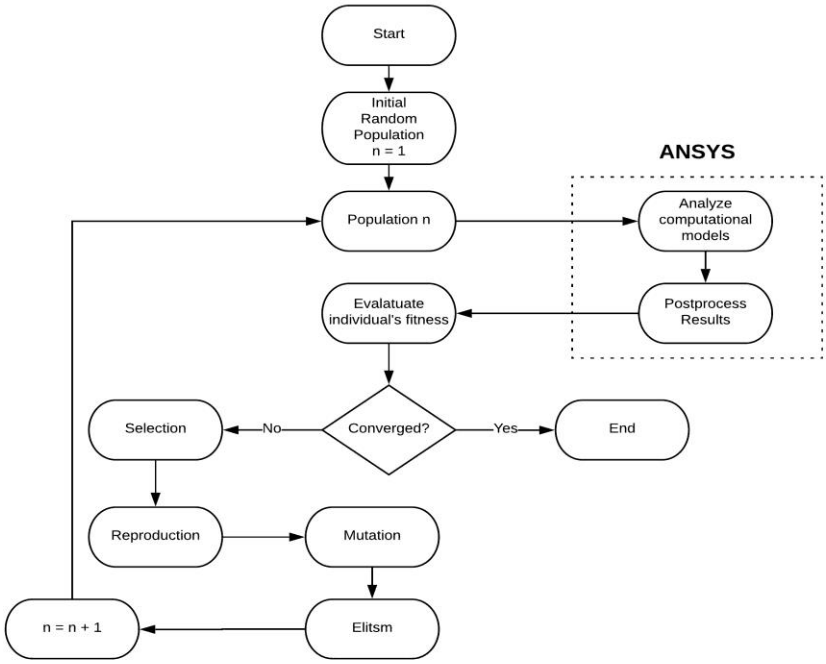

Fig. 2 Flowchart of the implemented Genetic Algorithm.

To represent the chromosomes, it was decided to use a real coding, where each gene associated with the chromosome is directly defined by the value of a degree of freedom of the problem. Figure 3 shows the general representation of a chromosome used in the present work.

As aforementioned, through Genetic Algorithms it is possible to determine which are the fittest individuals to a given problem. In order to do so, the parameter *fitness*, which is inversely proportional to the plate's central deflection, was defined as in Eq. 4. In other words, the smaller the central displacement of the plate, the greater its *fitness* and, hence, the capability of passing on its genes to the upcoming offspring.

$$fitness = \left(\frac{1-P}{U_z}\right) \quad (4)$$

being, U_z the central deflection of the stiffened plate and P a penalty imposed to individuals that violate the constraint regarding the maximum allowed height of transverse and longitudinal reinforcements.

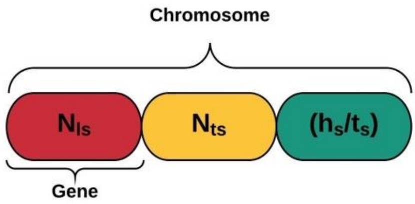

Fig. 3 Representation of a chromosome.

According to [13], the application of penalties is a widespread technique when dealing with restrictions in optimization problems. In order to deal with the restriction imposed on the stiffeners height, the penalty P was defined as:

$$a = \left(\frac{h_s - h_{s,lim}}{h_{s,lim}}\right) + 0.10 \tag{5}$$

$$P = (a, 0.95) \tag{6}$$

being $h_{s,lim}$ the maximum allowed height, which, in the present study, was defined as 0.3 m.

Through Eqs. (5) and (6), one can observe that the penalty P lies on the interval [0.10; 0.95]. These values were determined after successive test during the algorithm implementation.

In the selection genetic operator, a portion of the population (parents) is selected to generate new individuals (offspring) through the reproduction. The tournament technique was used because it offers numerous advantages over equally popular methods, as being more efficiently implementable and enabling to easily adjust the selection pressure [14]. In this selection method, a given number of individuals t_{size} is randomly selected from the population then the individual with the greatest *fitness* is used on the reproduction operator. In this work, the tournament size was defined as 5.

The reproduction genetic operator allows the exchange of desired characteristics between individuals. Since the analyzed degrees of freedom are discrete, a discrete reproduction was used as in [15]: being $x = \{x_1, \ldots, x_n\}$ and $y = \{y_1, \ldots, y_n\}$ the parents selected through the tournament. Then, the offspring $z = \{z_1, \ldots, z_n\}$ is given by:

$$z_i = \{x_i\}\ ou\ \{y_i\} \tag{7}$$

where, x_i or y_i are selected with a probability of 50%.

Moreover, mutation is responsible for performing minor alterations in the individuals generated on the reproduction. For that, uniform mutation was adopted, where the operator changes the value of a selected gene to a random value located between the upper and lower limits of that gene [11]. The mutation rate was considered as 0.10.

The elitism strategy was applied seeking to assure that the best individuals remained on the population of possible solutions. This strategy was employed analogously to Deb et al. [16] on their work about multi objective problems optimization using genetic algorithms: being P_t the population of N parents and Q_t their N offspring, both populations are combined in such a way that we obtain $R_t = P_t \cup Q_t$ with size $2N$. Then, elitism is applied to R_t and the N most fitted individuals are selected to the next generation. It is important to highlight that in all performed simulations a population with N = 20 individuals was adopted.

4. Computational Modeling

The computational modeling of the analyzed stiffened plates, as aforementioned, was performed on ANSYS® *Mechanical* APDL, through the Finite Element Method (FEM). For the numerical simulations, the finite element SHELL281, which is a shell element that has 6 degrees of freedom on each of its 8 nodes. In Troina et al. [17] and Cunha et al. [18], it was shown that discretizing stiffened plates using this element leads to satisfactory results regarding the deflection on the analyzed structural component.

Regarding the mesh refinement utilized in the simulations, four different meshes densities were considered: M1, M2, M3 and M4; where the finite element size of each mesh was a fraction of the plate's width (M1: $b/20$, M2: $b/40$, M3: $b/60$, M4: $b/80$). The mesh considered as independent was the mesh M3 and therefore quadrilateral shell elements measuring 16,67 mm were used in the simulations.

For brevity's sake, more information about the computational model of the stiffened plates numerical simulations, its verification as well as the mesh convergence test can be obtained in [8,17,18].

5. Results and Discussion

As aforementioned, the verification of the GA was performed considering 5 different values for the volume fraction ϕ: 0.1, 0.2, 0.3, 0.4, and 0.5. Since GA is a stochastic method, the experiment using the implemented algorithm was executed five times for each analyzed case. Figs. 4, 5, 6, 7, and 8 show the convergence through the generations to the optimal value obtained by Troina [8] where the *fitness* values of the most fitted individuals are a average of the 5 runs.

As one can notice in the presented graphs, through the genetic algorithm, it was possible to determine the optimal geometric configuration for each analyzed case. The best result was obtained for $\phi = 0.1$, where the convergence was reached on the fifth generation of individuals, while $\phi = 0.5$ presented the slowest convergence, on the tenth generation.

Based on the data obtained through the performed optimization processes, Tab. 1 shows a comparison between Exhaustive Search, performed by Troina [8], and Genetic Algorithm with respect to the amount of required numerical simulations to determine the geometric configuration that minimizes the central deflection of the stiffened plates.

It can be observed, in all studied cases, that the optimization using GA demanded the analysis of a smaller amount of geometries in comparison with ES. It was observed reductions on the number of required simulations varying from 24.24%, for $\phi = 0.5$, and 47.09%, for $\phi = 0.1$. Thus, the geometric optimization technique that utilizes an evolutive strategy proves itself to be more efficient than ES on the central deflection minimization of plates reinforced by stiffeners.

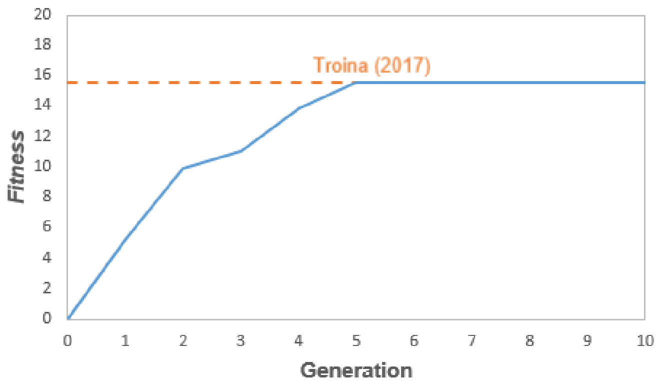

Fig. 4 Convergence for $ø$ = 0.1

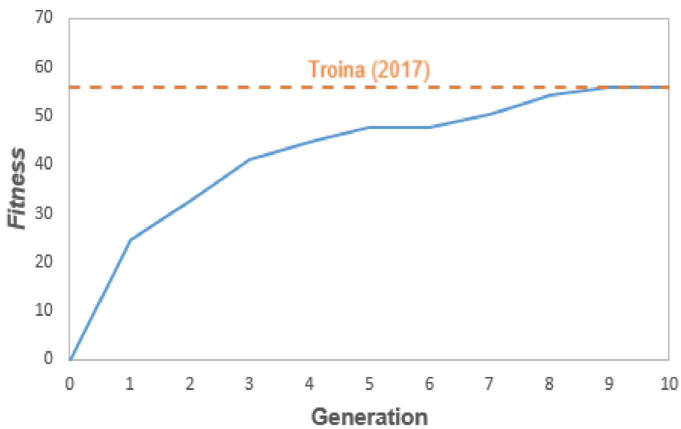

Fig. 5 Convergence for $ø$ = 0.2.

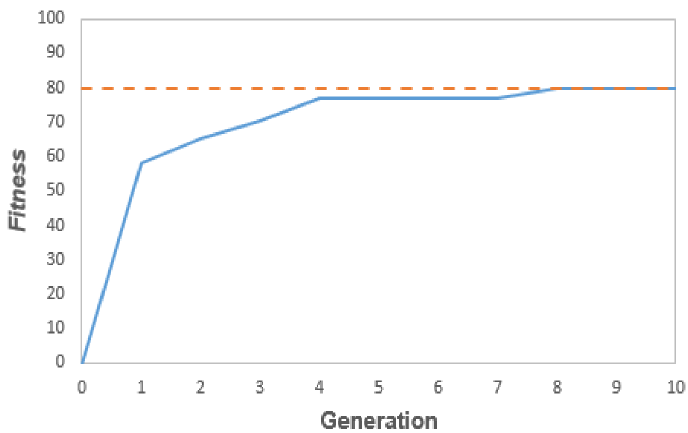

Fig. 6 Convergence for $ø$ = 0.3.

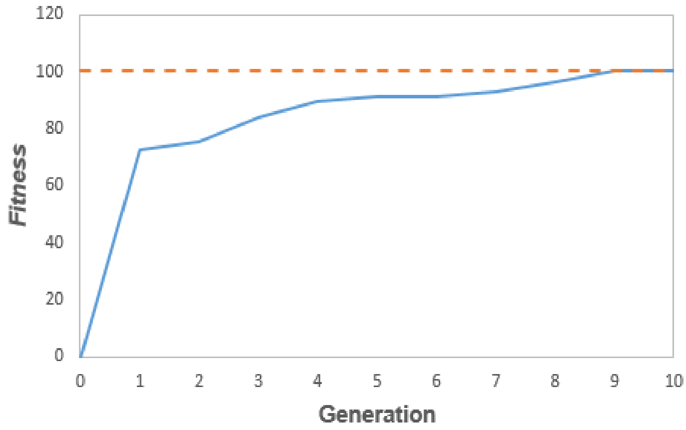

Fig. 7 Convergence for ø = 0.4.

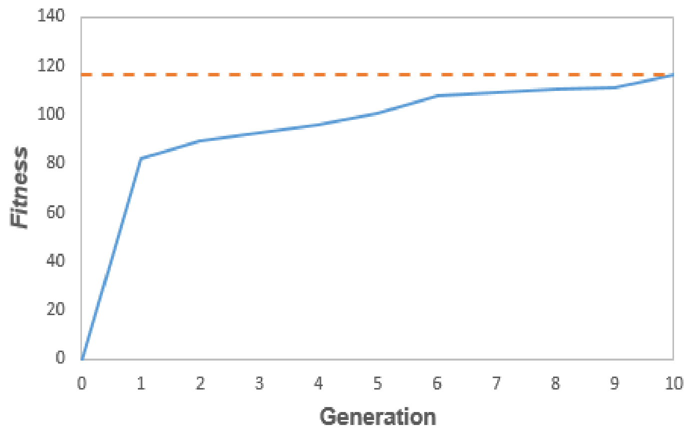

Fig. 8 Convergence for ø = 0.5.

Table 1. Comparison between ES and GA

	Exhaustive Search				Genetic Algorithm			
ø	Optimal configuration			Nº of performed simulations	Optimal configuration			Nº of analyzed individuals (average)
	N_{ls}	N_{ts}	(h_s/t_s)		N_{ls}	N_{ts}	(h_s/t_s)	
0,1	2	3	56,66	189	2	3	56,66	100
0,2	2	5	88,21	237	2	5	88,21	180
0,3	2	5	59,41	252	2	5	59,41	160
0,4	2	5	44,40	256	2	5	44,40	180
0,5	2	5	35,03	264	2	5	35,03	200

6. Conclusion

The viability of applying GA, allied with the Constructal Design Method and computational modeling, on the geometric optimization of stiffened plates with respect to the central deflection was ascertained.

Moreover, it was noticed that, for all analyzed cases, the genetic algorithm was more efficient than the exhaustive search since the former requires a smaller amount of simulations to determine the optimal geometry, being possible to reach a reduction of up to 47.09% on the number of analyses and hence there is a significant reduction of the demanded processing time of the optimization.

Another advantage of GA over ES is that the former, when the stop criterion is reached, provides a family of feasible designs. Since it is not always possible to manufacture the best individual, for practical reasons, the designer can choose any solution of the last generation of individuals without significantly affecting the solution quality. On the other hand, when using ES, this is not possible due to the wide dispersion of possible solutions.

On future works, it is intended to extend the performed analysis and evaluate the influence not only of the number of stiffeners and the ratio h_s/t_s but also other degrees of freedom. Moreover, through the application of Genetic Algorithms it is possible to execute multi objective optimizations, considering the deflections as well as the stresses that act upon the stiffened plate.

7. Acknowledgments

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