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A comparative study of genetic algorithms for the multi-objective optimization of composite stringers under compression loads

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ABSTRACT

Optimization methods are close to become a common task in the design process of many mechanical engineering fields, specially those related with the use of composite materials which offer the flexibility in the design of both the shape and the material properties and so, are very suitable to any optimization process. While nowadays there exist a large number of solution methods for optimization problems there is not much information about which method may be most reliable for a specific problem. Genetic algorithms have been presented as a family of methods which can handle most of engineering problems. However, starting from a common basic set of rules many algorithms which differ slightly from each other have been implemented even in commercial software packages. This work presents a comparative study of three common Genetic Algorithms: Archive-based Micro Genetic Algorithm (AMGA), Neighborhood Cultivation Genetic Algorithm (NCGA) and Non-dominate Sorting Genetic Algorithm II (NSGA-II) considering three different strategies for the initial population. Their performance in terms of solution, computational time and number of generations was compared. The benchmark problem was the optimization of a T-shaped stringer commonly used in CFRP stiffened panels. The objectives of the optimization were to minimize the mass and to maximize the critical buckling load. The comparative study reveals that NSGA-II and AMGA seem the most suitable algorithms for this kind of problem.

1. Introduction

The use of optimization methods in the design of structural components has been growing in the last years and becoming a usual step in the mechanical engineering workflow of many companies, specially those focused on aircraft/aerospace composite structures whose characteristics frequently meet the paradigm of a standard multiobjective optimization problem. For this reason, a large amount of optimization strategies ([1–5] among others) are available in the literature nowadays.

A structure of special interest which has been the object of optimization routines are composite panels stiffened with stringers. The optimization of the set panel-stringer is of high interest since this kind of structure is widely used in the aircraft industry. For them, Genetic Algorithms (GAs) [6], a family of evolutionary algorithms, have been successfully used, as reported in a large number of publications [7–11] among others. A case of special interest reported in the scientific literature is the optimization of the stacking sequence of composite laminates, for which GA have been used successfully [12,13]. However, in situations where the stacking sequence cannot be considered as a design variable but a imposed requirement, the minimization of the weight is achieved with geometrical parameters [14,15]. In that case, what makes different the optimization of composite structures from other materials is the use of failure mode based failure criteria such as Puck's [16] and LaRC [17]. These are in fact a set of failure criteria which assign a different index for the different failure modes under consideration. When they are included in optimization routines as non-smooth discontinuous constraints, the resulting optimization problem is very specific of composite materials, as can be concluded from some works analyzing the effect of different failure criteria in the optimal solution [18–20].

The original formulation of GAs is based on the concept of natural evolution: the survival of the fittest member, i.e., the better adapted members have more possibilities to transmit their characteristics to future generations. The translation of this strategy into an algorithm is performed by means of three operators:

- *Selection operator* which selects individuals with high fitness to form the mating pool.
- *Crossover operator* which permits the exchange of some characteristics between two or more members of the mating pool. Two individuals, called parents, exchange some characteristics to generate two new members, called children.

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- *Mutation operator* is implemented to save the process of losing genetic information during crossover. Random changes are applied in some individuals during the mutation process to preserve diversity in the population.

Although these three operators are the basis of a GA, there exist a large number of variations which implement different encodings, different selection operators, different methods for mating pairs or different strategies for mutation [21]. The behavior of a specific GA depends on the studied problem [22,23] and the design variables [24], for this reason, some previous experience or some comparative analysis is needed for selecting one GA out of a set of implemented GAs. Some comparative studies of evolutionary algorithms with different industrial cases have been already carried out [25,26], for example. These studies reveal that the best GA is different for each kind of problem.

A good choice when using GAs for the optimization of composite stiffened panels is a GA specifically designed for them, for example [27] and [28]. However, most of engineers are not familiar with the implementation of such algorithms and a commercial software with the most common GAs already implemented is a recommended option to carry out the optimization. In that case, a comparison of the most used GAs is a necessity for the choice as well.

The solution of the multi-objective optimization problem is linked to the concepts of dominance and non-dominance. When an individual is non-dominated it is a member of the Pareto's front, which is the set of possible optimal solutions. A candidate to solution **A** dominates candidate **B** if the conditions of Eq. (1) are fulfilled. On the other hand, if the Eq. (2) is satisfied **A** and **C** are considered non-dominated candidates.

$$f_i(\mathbf{A}) \prec f_i(\mathbf{B}) \leftrightarrow (f_1(\mathbf{A}) < f_1(\mathbf{B})) \wedge (f_2(\mathbf{A}) < f_2(\mathbf{B})) \quad (1)$$

$$f_i(\mathbf{A}) \sim f_i(\mathbf{C}) \leftrightarrow ((f_i(\mathbf{A}) \nless f_i(\mathbf{C})) \wedge (f_i(\mathbf{A}) \ngtr f_i(\mathbf{C})) \quad (2)$$

In this paper a comparative study of composite stringers under compression loads with three different GAs is carried out. The chosen three, implemented in software Isight™ [29], are: Archive-based Micro Genetic Algorithm (AMGA) [30], Neighborhood Cultivation Genetic Algorithm (NCGA) [31] and Non-dominate Sorting Genetic Algorithm II (NSGA-II) [32]. The main differences between these GAs are listed below:

- *NSGA-II*: After the creation of the parent population, sorting based on the non-dominance is used. A fitness (equal to non-domination level) is fixed in each solution. The best individuals of this ranking are used to create the new population using the selection, crossover and mutation operators.
- *AMGA*: This algorithm uses a small population size and creates an external archive with the best solutions obtained, which is updated every iteration. AMGA employs the concept of the non-dominance ranking of NSGA-II and it creates the parent population from the archive with the method of SPEA2 [33]. The mating pool is a derivation of the binary tournament selection method of NSGA-II. The use of the archive permits to obtain a large number of non-dominated points at the end of the simulation. AMGA is a GA highly based in NSGA-II.
- *NCGA*: A neighborhood crossover mechanism is added in the normal mechanisms of GAs which it improves the crossover operator. The pair of individuals to perform crossover is not randomly chosen, but the individuals who are close each other in the objective space are selected.

A T-shape stringer is used as a benchmark because of its simple geometry with only two design variables (Section 2.1) and because of its real-life interest in the design of stiffened panels. A preliminary study of the stringer is performed (Section 2.3) which permits to know the approximated optimal result. These structures are used for their compression behavior with low weight. For this reason, the objectives are both the maximization of the critical buckling load (P_{cr}) and the minimization of the stringer mass (m). In these cases, P_{cr} normally is most important for these structures and their design is in function of it. Then, in the optimization process is prioritized the P_{cr} than the mass (details in Section 3). Therefore, the previous optimal result is compared with the optimization results (Section 4) to know the reliability of the GA. Finally, a GA is proposed to use in the solution of similar multi-objective optimization problems.

2. Benchmark problem

2.1. Specimen

In this study a composite material T-shape stringer has been analyzed under compression load (Fig. 1). This geometry was selected since it provides both simplicity to run a benchmark and real life engineering interest.

The stringer is made from AS4/8552 pre-preg whose properties are described in Table 1. Stacking sequence is $[0/90/0_2/\pm45]$ for the stringer base and $[\pm45/0_2/90/0]_S$ for the stringer rib.

2.2. Virtual test

To carry out the optimization, a virtual test was modelled, using ABAQUS™ (Fig. 2). A compression load is applied on an end of the stringer and clamped by the other end. This compression load is applied by means of pottings, metallic elements where the stringer can be introduced and fixed with resin (Fig. 2). A potting only permits the displacement of the stringer base in X-axis and Y-axis in stringer rib. In the middle of the specimen a damaged zone was introduced to simulate the effects of an impact. This damaged zone is located in the stringer rib, in the middle of the specimen and it is modelled by reducing in a 50% the values of E_{xx} and X_C. The location of the damaged zone and the amount of properties reduction were obtained in a previous study [34]. It is added to simplify the finite element analysis (FEA) and to set the region where the first ply failure will appear. LaRC failure criteria is applied only in damaged zone to reduce computation time because it is known that the first ply failure will appear in the previously damaged zone. The elements used in mesh are S4 shell type (4-node shell element with full integration).

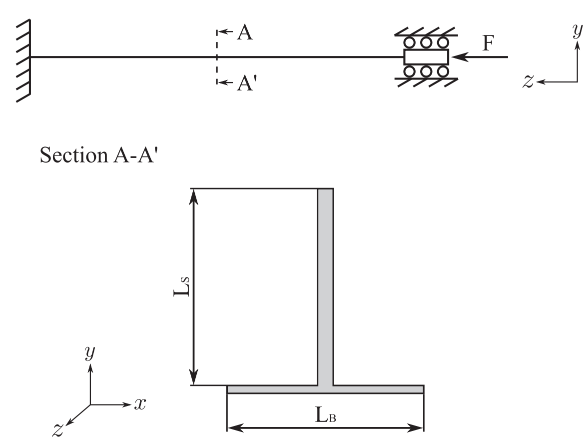

Fig. 1. Stringer section and schematic representation of the test.