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A numerical methodology for optimizing the geometry of composite structural parts with regard to strength

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ABSTRACT

The increased use of composite materials in lightweight structures has generated the need for optimizing the geometry of composite structural parts with regard to strength, weight and cost. Most existing optimization methodologies focus on weight and cost mainly due to the difficulties in predicting strength of composite materials. In this paper, a numerical methodology for optimizing the geometry of composite structural parts with regard to strength by maintaining the initial weight is proposed. The methodology is a combination of the optimization module of the ANSYS FE code and a progressive damage modeling module. Both modules and the interface between them were programmed using the ANSYS programming language, thus enabling the implementation of the methodology in a single step. The parametric design language involves two verifications tests: one of the progressive damage model against experiments and one of the global optimization methodology performed by comparing the strength of the initial and the optimum geometry. There were made two applications of the numerical optimization methodology, both on H-shaped adhesively bonded joints subjected to quasi-static load. In the first application, the H-shaped joining profile was made from non-crimp fabric composite material while in the second from a novel fully interlaced 3D woven composite material. In the optimization of the joint's geometry, failure in the composite material as well as debonding between the assembled parts was considered. For both cases, the optimization led to a considerable increase in joint's strength.

1. Introduction

As the use of composite materials in aircraft structures has exceeded 50% of the entire structure (52% in Airbus A350), the need for optimizing the composite structural parts with regard to strength, weight and cost has become imperative. The majority of reported optimization methodologies focus on weight and cost, mainly due to the difficulties in predicting strength of composite structures.

In the reported optimization methodologies related to strength [1–13], the shape of the composite part, the stacking sequence and the layer properties have been considered as design variables. In [1] a micro-genetic algorithm was used to design the stacking sequence of a carbon fiber reinforced composite automotive lower arm with regard to its performance. The performance of the optimized composite lower arm was verified using the static Risk analysis technique. In [2] presented is 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. The objective of [3] was to describe the concept of genetic algorithms in layout optimization of composite structures. The layout optimization was done with respect to stacking sequence, shape and total volume of the material. A multi-objective optimization methodology which simultaneously considers the mechanical performance, in terms of stiffness, and manufacturing cost of composite laminates was proposed in [4]. In [5] it was analyzed how different the optimal structures become when different first ply failure criteria are considered in the optimization of laminated composites. Two problems were solved: the minimum weight and the minimum material cost of laminated plates subjected to inplane loads. The

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failure criterion was taken into account by means of constraints introduced in the optimization problem. The results show that optimal structures highly differ when different failure criterion are considered and that none of the failure criteria is always the most or the least conservative when different load conditions are applied. In [6] a 3-D finite element analysis has been conducted to get an optimum composite patch shape applied on an inclined center cracked panel, repaired by symmetrical patch. The patch shapes considered are circle, rectangle, square, ellipse and octagon. Also SIF reduction is compared for the same volume of patch. It was observed that extended octagonal patch shape performs better in case of SIF reduction.

In [6] a generic method for the design optimization of laminated composite components was developed based on the vector evaluated particle swarm optimization algorithm. The algorithm was successfully implemented for the multi-objective optimization of composite materials. The same optimization problem was solved in [7,8] using the artificial bee colony and the quantum behaved particle swarm optimization methods, respectively. A technique for the design optimization of composite laminated structures was deployed in [9]. The optimization process was performed using a genetic algorithm associated with the FE method. Weight minimization on laminate composite plates subjected to in-plane loading took place in [10]. The optimal design was investigated using direct search simulated annealing while fiber orientation angles and layer thickness was chosen as design variables. In [11] the stability analysis of a vertically standing or hanging composite column under end force and distributed axial load was made. The composite column had varying cross-section and variable material properties. The integral equation method was formulated to deal with this problem. In [12] a neural network was implemented onto a 3-step procedure for the optimization of composite plates with discrete varying stiffness. Finally in [13], a two-scale topology optimization algorithm was proposed by using the bi-directional evolutionary structural optimization method for the concurrent design of the macrostructure and its composite microstructure. From the above short literature overview it is concluded that in the area of optimization of composite structures the research effort has been mostly placed on the development of single- and multi-objective optimization algorithms. Moreover, in cases where the performance has been considered as the objective function this has been done in terms of stiffness and stress rather than strength.

Among the most critical areas of composite structures that need to be optimized are joints. While optimization of mechanically fastened joints has reached to a threshold and the process of reinforcing the existing fastened configurations has started [14], optimization of adhesive bonded joints is a basic function of the redesign process required for the realization of adhesive bonded joining. There are a few reported works in this area. In [15] a systematic procedure for minimizing the shear elastic stress concentration was presented. The proposed method was based on the tapering of adherents in a specific manner to achieve smooth stiffness transition and uniform shear stresses. Shape optimization of bonded joints was performed by the use of numerical shape optimization techniques in [16]. The aim of the study was to obtain joints that are as strong and light as possible under static loading conditions by changing the profiling of the adherents. Mathematical formulation for stress based optimization was proposed for 2D problems in [17,18] and extended for 3D structures in [19,20]. Campilho et al. [21] presented a 2D numerical analysis to assess the influence of several geometric changes on the tensile residual strength of repaired CFRP composite plates. Their model was validated by comparison with previously published experimental results. Haghani et al. [22] carried out a parametric study to investigate the effect of tapering length and the material properties of joint constituents, i.e., stiffness of the laminate and adhesive, on stress distribution in adhesive joints using the FE method. Labbé and Drouet [23] used a multi-objective optimization method to identify globally optimized configurations of bonded tubular single-lap (TSL) joints under bearing axial load.

A major conclusion that can be drawn from the above literature overview is that the existing optimization works on bonded joints and, more general, on composite structural parts have not considered strength. In the present work, a numerical methodology for optimizing the geometry of composite structural parts with regard to strength by maintaining the initial weight is proposed. The methodology, which is a combination of the optimization module of the ANSYS FE code and a progressive damage modeling module, can be applied to any composite structural part subjected to quasi-static loading conditions under the necessary modifications in the components of the methodology. The methodology was applied to two bonded joints realized by means of a novel H-shaped joining profile made from non-crimp fabric and 3D fully interlaced composite material.

2. Numerical optimization methodology

The algorithm of the numerical optimization methodology is described by means of the flowchart shown in Fig. 1. The methodology is divided into three basic routines: PDM of initial geometry, optimization and verification. Each of the routines is described in the following paragraphs.

2.1. PDM of initial geometry

At this step, the strength of initial geometry is predicted. As this step is decisive for the forthcoming analysis, the numerical results are verified against experiments and the necessary modifications on the PDM are made. A classical PDM comprises the modules of stress analysis, failure analysis and material property degradation. These modules are modified according to the geometry of the structural part, the loading conditions and the type of composite materials used. Stress analysis is performed using detailed 3D FE models. Failure analysis is performed using failure criteria established for unidirectional composites due to lack of failure criteria for woven fabric composites. The material property degradation module is highly material-dependent and sometimes needs to be modified in order to efficiently describe the material's response due to failure.

2.2. Optimization procedure

2.2.1. Algorithm

For conducting the optimization, the design optimization module of the ANSYS FE code [24] was used. The module employs three types of variables that characterize the design process: the design variables, the state variables and the objective function.

The design variables are independent variables which vary inside a certain range to achieve the optimum design. Variation of design variables has an effect both on state variables and the objective function. The vector of design variables is defined by:

$$\mathbf{x} = (x_1 x_2 x_3 \dots x_n) \tag{1}$$

Design variables are subject to n constraints with upper and lower limits, that is,

$$\underline{x}_i \leqslant x_i \leqslant \bar{x}_i \quad (i = 1, 2, 3, \dots, n) \tag{2}$$

where n is the number of design variables.

The dependent or state variables are response quantities that are functions of the design variables. A state variable may have