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Design for manufacturing of multi-material mechanical parts: A computational based approach

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Abstract

This study presents an approach to the mechanical design of multi-material parts, intending to provide the values of the involved design variables, such as reduced metal thickness, number of composite layers and layer orientation. The proposed method incorporates the Finite Element simulations into a Genetic Algorithm framework that aims to yield a multi-material part, with the minimum possible weight, whilst satisfying the imposed design requirements. An additional objective function, the minimization of the elastic energy, is introduced so as for the best fiber orientation of each layer to be acquired. A plate, subjected to uniform forces/moments, has been adopted in order for the effectiveness of the approach to be demonstrated. The results show that the upper limit to weight reduction is constrained by the yield strength of the metal component, hence its corresponding thickness. Based on the design configuration, weight savings up to 9% could be reached.

Keywords: Mulri-material, finite elements, design

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1. Introduction

An application of multi-materials is for the production of structural elements that have equal or increased performance and significantly lower weight, compared with their equivalent uni-material. However, accurate material design is required in order for high levels of mass reduction to be achieved. The critical design parameters, whose best values will be calculated, are the number of plies, stacking sequence and the metal thickness. According to [1], the four categories of optimization approaches of composite laminates are i) analytical methods, ii) numerical methods, iii) stochastic and heuristic search methods, iv) mathematical programming techniques, as well as combinations of the above. Important is the study of Schmit and Farshi [2], in which mathematical programming has been employed for the minimization of the mass, under strength and stiffness constraints, using layer thicknesses for pre-defined orientations as the design variables. Another important optimization method used for lamination parameters is the one presented in the work of Tsai and Pagano [3]. Moreover, the free material optimization of Ringertz [4] and the Discrete Material Optimization by Sigmund and Torquato [5] are studies that paved the way for the optimization of composite laminates. In [6], there is a presentation of a multi-directional constrained method for topology optimization. Moreover, recent advances in the design optimization field are [7], [8] and [9] made by Hvejsel and co-workers.

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However, those studies focus on the design procedure of composite laminates and not on the optimization of multi-material parts. A first attempt that supports the decision making of multi-material parts is presented in [10], in which a conceptual framework is proposed. The platform assists with the multi-material design, alongside with the planning of its related manufacturing processes. In such systems, a mechanical design module is utilized.

In this study, the structural design of multi-material components is approached with the use of Genetic Algorithms for the the process's automation. Furthermore, a numerical implementation of the developed mechanical design approach, presented through a plate example, has been presented.

2. Multi-material Parts: The best solutions

2.1. Problem Formulation

The problem of interest is schematically depicted in Figure 1: the metal of the reference part will be replaced by a composite/metal bi-material system. The best selection of the associated geometric parameters will lead to a bi-material component, with a reduced (the minimum possible) weight, compared to that of the metallic reference part, while simultaneously satisfying the imposed strength requirements for a given set of load cases. This goal is efficiently achieved by utilizing an optimization scheme, in cooperation with the structural Finite Element (FE) analyses. The problem's associated design variables are defined as t_m, which is the new reduced thickness of the bi-material metal component, n is the number of layers of the bi-material composite component and [θ_1, θ_2, θ_n] correspond to the angle orientation of each layer in the bi-material composite component.

It is considered that all plies are manufactured by the same material and have equal thickness t_l. A uniform fiber orientation has also been considered over the selected area of the multi-layer application. The fact that the number of composite layers n controls the size of the vector, containing the orientation of each ply, is apparent.

The corresponding orientation of each layer, as calculated from an isotropic material, is based on the fact that the fibers have to be parallel to the direction of the principal stresses.. Mathematically speaking, the best layer orientations minimize the material's strain energy. This property can be used in the problem's set-up by defining an objective function that will be minimizing the total elastic strain energy U, which is a function of the associated design variables also involving an integration of the stress and strain tensor product, into the component's total volume. It is important to be stated that the strain energy affects the grain growth of a metal part and in the case of thin films it has an even greater impact. As a result, the microstructure, which plays a major role in the determination of the mechanical properties of parts, is connected to the strain energy [11]. Other examples in which the strain based topology optimization method is used is the design of simple structures, namely the cantilever beams, or grippers, as well as much more complex issues, such as the design of energy absorbing structures (aerospace and automotive industry) [12].

The mass of the multi-material is controlled by the number of layers n and by the metal's thickness t_m. To this effect, an additional objective function that minimizes the total mass M of the bi-material component is introduced for the minimization of those two parameters.

The problem might be subjected to several constraints, associated with the design requirements, such as strength, displacement, stability requirement, etc. Without any loss of generality, in this study,, in which the stresses have to remain within the linear elastic region of the involved materials, only a strength requirement has been taken under consideration.

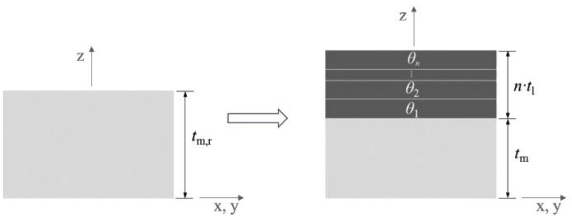

Figure 1. The problem of replacing a metallic material with a multi-material.

The von Misses yield criterion is used for the metallic material. It has to be noted that there are not yet universally agreed failure criteria for composite materials, due to their anisotropy and inhomogeneity [13], [14]. For this purpose, a Failure Index (FI), which is applied to some of the available failure criteria, for first ply failure calculation, is herein used. The FI based criterion is evaluated at each material point of each composite layer that is involved and failure does not occur as long as FI remains below unity. The generated design points (set of design variables), within the algorithm, are guided by the two objective functions and the two imposed design constraints. The optimization process that follows is depicted in Figures 2 and 3.

2.2. Numerical Implementation

Figure 3, presents the proposed framework that involves the FE and the Solution Modules. Due to the problem's nature, i.e. multiple objective functions and discrete design variables, the Genetic Algorithms (GA) have been employed. The framework functionality is ensured by having taken into account the defined design variables in the parameterization of the component's FE representation. The load cases are assigned over the FE mesh at this level, together with the corresponding loading and boundary conditions. The solution output parameters, defining the state variables and the objective functions, are further post-processed within the FE module. Next, they are fed into the Solution Module for evaluation. The algorithm will yield candidate design points from the wide design space, once the convergence criteria (e.g. maximum allowable Pareto percentage, convergence stability percentage, maximum number of iterations etc.) have been met for the up-