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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.

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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.

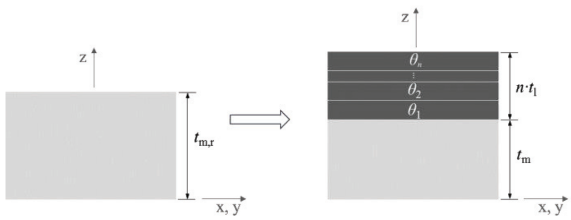

Figure 1. The problem of replacing a metallic material with a multi-material.

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-to-date sample sets. Alternatively, new sample sets of design points are generated until the algorithm has been converged.

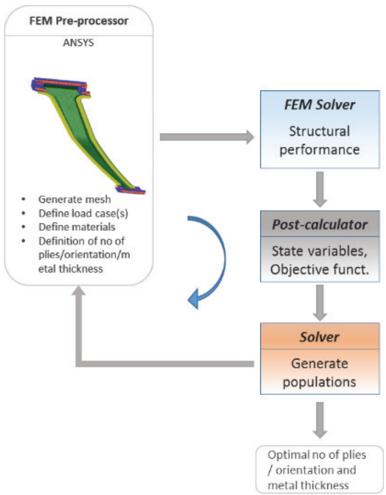

Figure 2. Schematic of proposed method

3. Method Implementation and Results

In Figure 4, there is a depiction of the example that has been considered for the numerical verification of the developed scheme. Its overall aim is the replacement of the metallic material with a composite/metal multi-material, which will have the least possible weight and will simultaneously satisfy the strength requirements. This will be achieved by following the proposed multi-material design process in order for the best set of parameters to be reached.

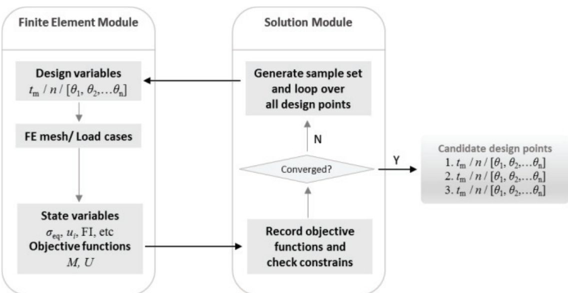

Figure 3. Proposed framework.

Worth mentioning is the fact that the geometry remains constant and only the cross sectional parameters (design variables) have been considered in the scheme. The plate is uniformly stressed in both the in-plane directions (x and y) when it is subjected to uniform axial loads and bending moments, as shown in Figure 4.

Initially, FE simulations were performed bearing in mind that the corresponding parts were fabricated only by metallic material, in order for an arbitrary set of loads/moments, which would lead to the yield strength of the metal plate to be evaluated when subjected to it (see metal properties in Table 1).

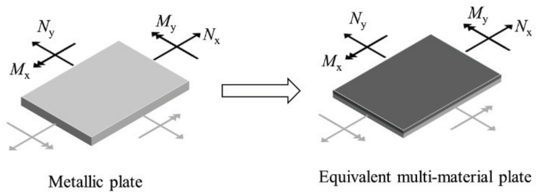

Figure 4. Metallic plate subjected to uniform forces and moments and its multi-material equivalent (composite layers bonded to reduced thickness metallic plate).Dimensions Lx:1000mm, Ly:500mm, tm:10mm, Load: Nx = -10e3 N, Ny=10e3 N, Mx=2e6 Nmm, My=3.6e6 Nmm.

Given the relatively thin cross section of the adopted geometries, the FE discretization has been based on 8-node shell elements (Shell 281 element available in the ANSYS element library). Modelling with shell elements is advantageous because of the fact that the design variables ($t_m, n, \theta_1, \theta_2, \dots, \theta_n$) are explicitly equivalent to the cross sectional data used for the definition of the mesh properties. As a result, such FE models are highly efficient, with an accelerated solution time of the scheme, compared to that of detailed FE meshes with solid elements.

The proposed framework, based on the calculated design loads, was next employed within the proposed multi-material design process. The unidirectional Carbon Fiber Reinforced Thermoplastic (CFRT) with ply thickness, equal to 0.18 mm [15], is the composite material that has been selected for this study. The corresponding elastic and failure material properties are listed in Table 1, [15]. A failure index (magnitude below 1.0 denotes that the ply does not fail), which is the maximum value of the available failure criteria in ANSYS v.17, as calculated at all material points and all plies [15] has been used in this study. Inputs and outputs of the analysis can be seen in Table 2.

The size of the design space is controlled by the number of design variables and the discrete levels per design variable (discretization density). In the case of a symmetrical stacking sequence, the size of the angle vector is reduced to half compared to that of an unsymmetrical composite.

The level of exploration of the design space is directly associated with the population numbers (number of initial and per iteration samples), which are set by the user in the Multi-Objective Genetic Algorithm (MOGA) scheme, together with the discretization density and number of design variables.

Table 1. Material properties for metal and UD composite, where E_1 and E_2 are the Young's Modulus in the fiber and transverse direction, respectively, v_{12} and v_{21} are the major and minor Poisson ratios, respectively, G_{12} is the in-plane shear modulus, X_t and X_c are the tensile and compression strength along the fiber direction, respectively, Y_t and Y_c are the tensile and compression strength along the fiber direction, respectively, S is the in-plane shear strength, E is the Young's modulus of the metal, v is the Poisson ration of the metal, S_y is the metal's yield strength.

E_1 (MPa)	E_2 (MPa)	v_{12} (MPa)	v_{21} (MPa)	G_{12} (MPa)
178e3	9e3	0.27	0.02	5.2
X_t (MPa)	X_c (MPa)	Y_t (MPa)	Y_c (MPa)	S (MPa)
3050	1500	80	250	94
E (MPa)	v (-)	S_y (MPa)		
210e3	0.3	400		

It has been shown by parametric runs of the scheme that the discretization density of the design variables has a significant influence on the resulted candidate sets (best set of design variables) and subsequently, on the corresponding mass reduction.

The interpretation of the results, allows for a correlation of the maximum normalized equivalent stress (max σ_{eq} /S_y) with the metal thickness t_m and the percentage mass reduction. It is evident that the level of mass reduction is controlled by metal utilization (max σ_{eq} /S_y =1 corresponds to full utilization of the meta). In other words, the best design, which corresponds to the minimum weight of the bi-material component, is constrained by the yield strength of the metal material. The failure index of the composite material, in all of the solutions, remains at low levels, thus proving that a constraint that is the factor guiding the algorithm, in order for the minimum solution to be reached, is the strength of the metal. The obtained stacking sequence is an outcome of the minimization of the strain energy that converged together with the mass minimization objective function.

In all numerical solutions, the failure index of the composite material remains at low levels, proving that the metal-strength-constraint is the factor that guides the algorithm for attaining the minimum solution. Given the performed solutions, the best bi-material design could not exceed a mass reduction of 9%. The obtained stacking sequence from each solution is the outcome of the minimization of the strain energy that converged together with the mass minimization objective function. The candidate sets, having resulted, include 12 composite layers, with stacking sequences, comprising 0° and 90° orientations in different arrangements. This output qualitatively agrees with the principal stress directions, obtained from the solution of the reference metallic case. From the design's point of view, the best fiber orientation direction is the one being parallel to the direction of the principal stresses, calculated through a homogeneous and isotropic material.

Table 2. Input parameters and obtained results for the design configuration examined for the example.

Variable	Input discrete values		
n	[6, 8, 10, 12]		
t_m	[8.0, 8.2, 8.4, 8.6]		
θ_i	[0, 15, 30, 45, 60, 75, 90, 105, 120, 135]		
Cand. sets	(t_m, n, θ_1, θ_2,…, θ_n)	Max σ_{eq} /S_y	Mass red. (%)
1	(8.6, 12, [[0/90]3]s)	0.98	9

4. Conclusions

The topic of this study is the development of a structural design approach to multi-material components. The proposed scheme is implemented into the ANSYS FE commercial software and its application to a composite/metal bi-material example is presented. Based on the adopted procedure, several major conclusions have been derived. More specifically, the minimization of the component's strain energy, having acted as one of the objective functions of the algorithm, efficiently leads to the best stacking sequence of the composite material. Furthermore, important is the fact that the discretization density (number of discrete levels per design variable) has affected the size of the design space and as a result, it must be carefully set, in order for the best design variables to be reached. In addition, the level of mass reduction is constrained by the strength-of-the-metal-requirement and hence its corresponding thickness.

The proposed method can also be utilized for the maximization of other KPIs without any loss of generalization. This can be achieved by using an objective function that describes a different manufacturing aspect, such as thermal deflections or residual stresses. The procedure that has to be followed for the minimization or maximization of such a function is the same as the one described in this study.

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References

[1] Fang, C., & Springer, G. S. (1993). Design of composite laminates by a Monte Carlo method. Journal of composite materials, 27(7), 721-753.

[2] Schmit, L. A., & Farshi, B. (1973). Optimum laminate design for strength and stiffness. International Journal for Numerical Methods in Engineering, 7(4), 519-536.

[3] Tsai, S. W., & Pagano, N. J. (1968). Invariant properties of composite materials (No. AFML-TR-67-349). Air Force Materials Lab Wright Patterson AFB Ohio.

[4] Ringertz, U. T. (1993). On finding the optimal distribution of material properties. Structural Optimization, 5(4), 265-267.

[5] Sigmund, O., & Torquato, S. (1997, February). Design of materials with extreme thermal expansion using a three-phase topology optimization method. In Smart Structures and Materials' 97 (pp. 52-60). International Society for Optics and Photonics.

[6] Lu, J., & Chen, Y. (2012). Manufacturable mechanical part design with constrained topology optimization. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 226(10), 1727-1735.

[7] Hvejsel, C. F., Lund, E., & Stolpe, M. (2011). Optimization strategies for discrete multi-material stiffness optimization. Structural and Multidisciplinary Optimization, 44(2), 149-163.

[8] Hvejsel, C.G.; Muñoz, E. (2010): "Discrete Multi-material Optimization: Combining Discrete and Continuous Approaches for Global Optimization", to be submitted.

[9] Hvejsel, C.F.; Lund, E. (2011): "Material Interpolation Schemes for Unified Topology and Multi-material Optimization", Structural and Multidisciplinary Optimization, DOI: 10.1007/s00158-011-0625-z.

[10] Foteinopoulos, P., Stavropoulos, P., Papacharalampopoulos, A., Chryssolouris, G. (2016). Unified approach in design and manufacturing optimization of hybrid metal-composites parts, presented in the 5th CIRP Global Web Conference (CIRPe2016).

[11] Zielinski, E. M., Vinci, R. P., & Bravman, J. C. (1995). The influence of strain energy on abnormal grain growth in copper thin films. Applied physics letters, 67(8), 1078-1080.

[12] Lee, E. (2011). A strain based topology optimization method (Doctoral

dissertation, Rutgers University-Graduate School-New Brunswick).
[13] Kaddour, A., Hinton, M., Soden, P., 2004. A comparison of the predictive capabilities of current failure theories for composite laminates: additional contributions. Compos. Sci. Technol. 64, 449–476.
[14] Soden, P., Kaddour, A., Hinton, M., 2004. Recommendations for designers and researchers resulting from the world-wide failure exercise. Compos. Sci. Technol. 64, 589–604.
[15] ANSYS® Academic Research, Release 17, Help System, ANSYS, Inc.