ARCHITECTURE AND MATERIALS SELECTION IN MULTI-MATERIALS DESIGN

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Abstract

The design process involving both the architecture and the materials represents an hard task mainly due to the high number of potential configurations, thus requiring firstly the development of new and more rigorous approaches but also the development of new tools.

To this purpose, we present in this work a new strategy for the design of architectured materials. Such a strategy relies on one hand on the construction of some databases for the selection of both geometrical patterns and materials, and on the other hand on the use of well-known analytical models to describe the physical behaviour of the multi-material. In order to prove its effectiveness, we apply our strategy to the problem of the least-weight design of a multilayer plate that has to meet thermal, electrical and mechanical requirements. Moreover, we use a genetic algorithm, as a numerical tool, to perform the solution search for our problem. Numerical results show that we can obtain optimum configurations characterised by a weight saving up to 72% keeping the same (or even superior) thermal, electrical and stiffness properties than those of a monolithic reference plate.

1. Introduction

Designing an industrial product consists in determining all its characteristics: number of parts, geometry, dimensions, constitutive materials, manufacturing process, joining process, etc. Several studies were conducted in order to elaborate a strategy putting all these characteristics into the same design process by developing, for instance, different analytical methods like functional analysis, concurrent engineering or TRIZ.

Among these contributions, materials selection methods are based on three different approaches [1,2]:

(1) the free search method which explores the whole set of solutions;
(2) the questionnaire strategy which guides the designer by asking appropriate questions;
(3) the knowledge based system which uses the results of previous experience.

The fundamental principle of materials selection based on free searching lies on the quantitative evaluation of the performance of a material regarding the functions of the product. As the best solution is picked from a database, it offers better possibilities for innovation than the others. However, the use of performance index isn't so simple when designing a multi-material.

In accordance with the definitions proposed by Ashby, Bréchet or Kromm [3–5] a multi-material or an architectured material is considered to be the association of one or several materials disposed according to a predefined architecture such that a representative volume element has at least one dimension that is very small compared with the dimensions of the entire structure.

The parameters that the designer must define in the design of a multi-material are:

- the components, that are usually materials, or be semi-products (this is the case, for example, of multilayer structures or stratified composites);
- the volume fractions of the components;
- the architecture and morphology of the components, i.e. their spatial disposition;
- coupling modes between the components, especially the nature of the interfaces and their behaviour.

Previous studies have been carried out to find a way to determine some of these parameters. For example, a focus on the material requirements allows the division of the constraints in two sets of requirements, separating the incompatible ones [6]. Moreover, when the architecture of the multi-material has been chosen, the problem is reduced to the search of a proper combination of materials, but even in this case the number of configurations remains very high. To this purpose, in [7] the authors proposed a filtration method to determine all possible combinations of materials satisfying the constraints imposed to the problem. In this way the number of potential solutions, i.e. those configurations that are candidate to be solutions for the problem at hand is drastically reduced, thus, simplifying the solution search process. The aim of this paper is to show how the architecture of the multi-material can be selected by the designer. In a first paragraph, the general principle is described. Then, as this method is based on a free searching approach, an architecture database has been built. Finally, the numerical method for the choice of the optimal architecture and components is explained and validated on an example.

2. Basis for multi-material architecture selection

2.1 General principle of the selection method

The selection of the best material for an application consists in determining the optimal value of a combination of material properties called performance index. This indicator is derived from the expression of the performance of the product (mass or cost for example) in which all the parameters except the materials properties (i.e. geometrical or functional parameters) are fixed.

There are several ways to define the performance of architecture. For example, the improvement on a property (or combination of properties), i.e. the gain, could be calculated comparing it with a law of mixture with the same components and volume fraction. This principle is close to the shape factor [8,9] that is used to select the shape of the cross section of a beam. Another method consists in using shape optimisation algorithms like level set for example [10]. With this method, the architecture isn't picked from a database, but it evolves at each step of the calculation. The drawbacks of this method are that the final morphology depends greatly on the initial one, and that the computational costs times are very expensive. The method developed in this study consists in selecting the architecture from a database, as shown in figure 1. As the homogenised properties of this architectured material depend on the properties of the components, a material database is used too.

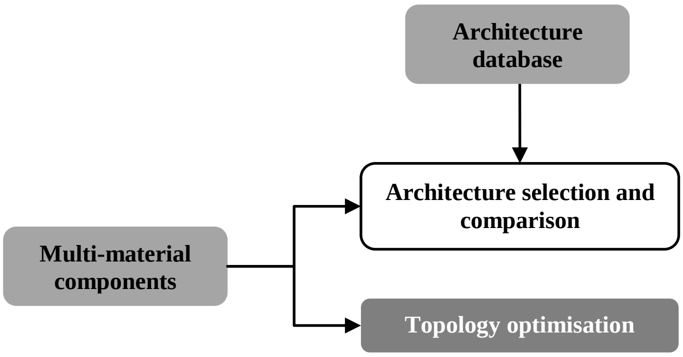


Figure 1. General method for architecture selection

The selection in a database allows a quick comparison of very different morphologies. Then, after a first ranking of the candidates, the parameters of the chosen architecture can be optimised thanks to classical topology optimisation methods in a final step.

Before starting the selection process, the architecture database has to be built, taking into account the important notion of hierarchy.

2.2 Architecture database

The database that must be created has to be representative of the various possibilities of the multi-materials, but doesn't have to be exhaustive because it just aims at illustrating the selection method and mustn't lead to important calculation times.

Trying to make a collection of the most classical architectured materials, it appears fundamental to create a hierarchy in the database. Indeed, multi-material morphologies can sometimes appear quite complex, but they can be considered as a combination of elementary patterns [11,12], so, the database has to be organized as a function of the length scale.

In a first time, at macroscopic scale, it is supposed here that all the multi-materials are multi-layered, so the only morphology that is considered in this category is a division of the material through the thickness.

Then, each layer can be filled with a predefined morphology. The possible elementary patterns have been separated in different types as illustrated in figure 2:

1) monolithic material;
2) composite material: matrix reinforced by particles, short or continuous fibers;
3) cellular material like foams or honeycombs;
4) functional patterns, i.e. segmented morphologies that allow a fluid flow circulation.

2.3 Homogenisation models

After the presentation of the most representative patterns, the corresponding homogenisation models have to be identified. The analytical homogenisation model efficiency is at the crossroads between the right choice of the number of geometrical parameters considered and their usability. A classification of the homogenisation models is for example made for the composite materials [13] following the parameters that are taken into account (morphology of reinforcement, statistical repartition in the matrix…). The chosen models for this study are limited to the second order, so that the parameters concern only materials properties, volume fractions, and geometrical factors that determine the morphology. The interfaces properties

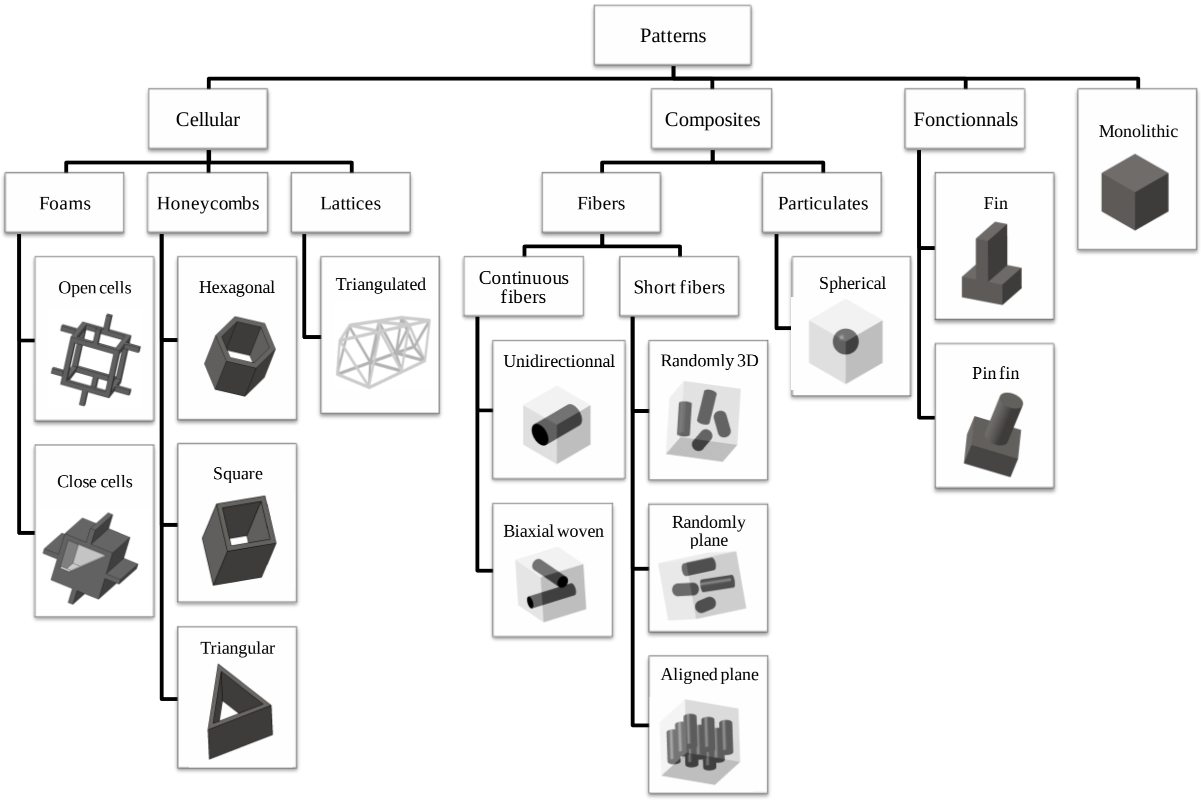


Figure 2. Hierarchical database of elementary patterns

are not taken into account as a design parameter, the layers are supposed to be perfectly bonded.

3. Numerical method for architecture and components selection

3.1 Definition of a candidate

In this study, 22 parameters have to be determined for each layer, with 8 to 100 levels depending of parameter. The available range of values associated to each parameter, and the step that is used to discretise these variables is an important aspect of the design. Indeed, the interval of variation must take into account the physical or technological limitations. While the chosen variation step must be high enough to limit the number of candidates and low enough to avoid the elimination of solutions because of a rough dimensioning.

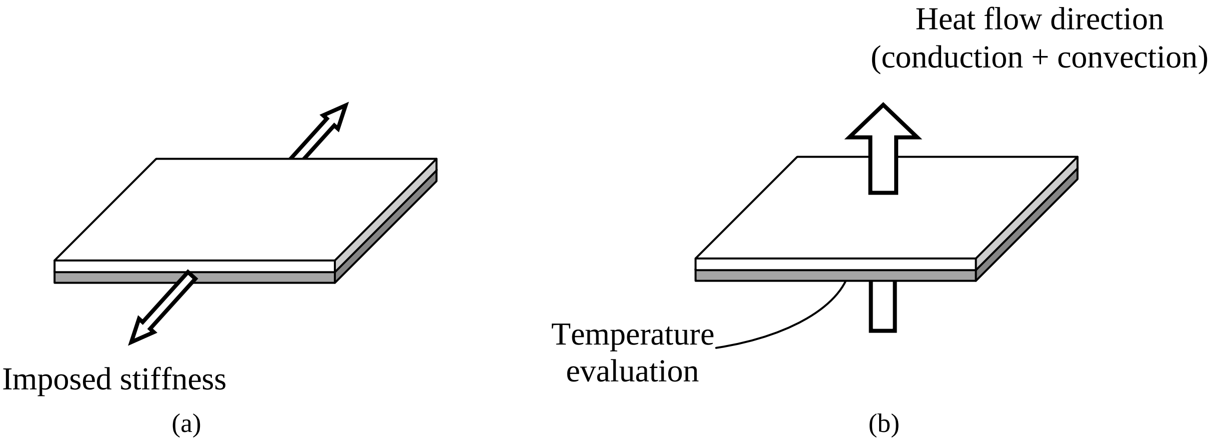
3.2 Evaluation and ranking of the solutions

The solution space is too big to allow a systematic screening because of the calculation time into play. The numerical method for the selection of the architecture and components has to deal with a lot of different parameters to evaluate the homogenised properties and performances. Some of these parameters are quantitative (volume fractions, particle dimensions…), but others are qualitative (type of architecture, constitutive materials…) so different kinds of variables have to be manipulated. In this case, previous studies showed that genetic algorithms can give optimum results in reduced times [14,15], so we chosed this numerical method.

4. Case study

4.1 Description of the design problem

The developed method has to be, firstly, validated on a basic case study. This example concerns the weight minimisation of a rectangular bi-layer plate, satisfying some design constraints on the in-plane tensile stiffness value along one direction (case 1) or two orthogonal directions (case 2), on the maximum temperature on the bottom face. This plate is submitted to a given transverse heat flow and an imposed in-plane electrical resistance, as illustrated in figure 3.



(a) (b)

Figure 3. Definition of the design constraints for (a) mechanical and (b) thermal functions

The transverse heat flow is imposed on the lower side of the plate with a value equal to 900 W/m^2. The thermal modelisation takes into account the heat conduction through the plate, and the convection on the upper face. As the convection coefficient depends not only on the air flow but on the geometry of the surface, it is attributed a value of 16 W/K.m^2 for a plane surface, but has to be calculated when the upper layer of the material is constituted of fins [16,17]. A maximum temperature on the lower side plate is required smaller than 363 K. For both cases 1 and 2 of mechanical loads, a tensile stiffness is needed greater than 1.385 10^8 Pa.m. Finally, electrical resistance along the length direction of the plate is required smaller than 2.10^{-3} Ω.

4.2 Optimal solutions for the problem

To solve the problem, we used the genetic algorithm BIANCA [18,19] which can handle, within the same problem, variables of different nature: continuous, discrete, scattered and abstract. Depending on the various mechanical loads imposed, i.e. case 1 or 2, the following results were obtained. For comparison of the results, reference is made to a thin 2 mm thick plate made of aluminium alloy dimensions 250 mm x 110 mm covered with pin fins as illustrated in figure 4: the plate thickness allows to exactly satisfy the stiffness constrain while the pin fins allow a sufficient convection satisfying the thermal constrain (it can be noticed that other geometric parameters of pin fins could be chosen for the selected reference case but the mass gain, if there would be, would be negligible given the total mass of plate). Aluminum alloy is itself sufficiently thermally and electrically conductive to provide the required thermal conduction through the thickness and the in-plane electrical conductivity. From table 1 results, it can be noticed that the genetic algorithm shows in a first part, a good

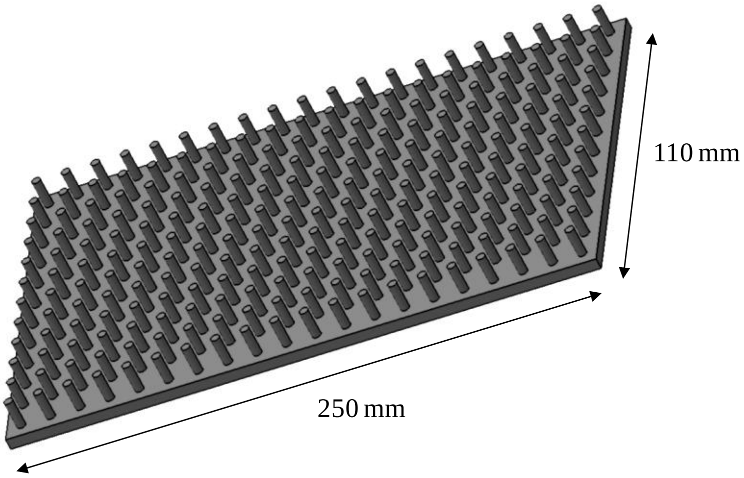


Figure 4. Reference plate used for results comparison

matching in the architecture choice responsive to a mechanical load change and in second part, a significant weight gain. Moreover, these architecture/materials couple selection were obtained in a reasonable time (a few minutes).

5. Conclusions

That work was carried out within the MUJU project framework financed by the National Research Agency (ANR-11-0003-RMNP).

A method allowing the selection of the architecture and components of a multi-material has been developed. Thanks to a database presenting the most classical architectures and to a material database, the genetic algorithm used in this work has been able to propose optimised solutions in a very short time with respect to the number of potential solutions. This method has been validated on a schematic example lying on mechanical, thermal and electrical

		Layer top 1	***Layer bot 2***	***% Weight gain***
Case 1	Architecture	Pin-fin	Unidirectional fibers	72.57
	Materials	Magnesium alloy	Carbon UHM fibers/Magnesium alloy matrix	
Case 2	Architecture	Pin-fin	Biaxial woven	69.05
	Materials	Magnesium alloy	Carbon pitch fibers/Magnesium alloy matrix	

Table 1. Results of the optimisation calculations

constraints. The results illustrate the adaptability of the multi-materials, giving different optimal solutions when constraints were changed.

In order to make this selection more precise, it would be interesting to establish filtration criteria for architectures and components, so that the solution space would be narrowed. With an efficient method, the reduced number of candidates would allow a complete screening with smaller variation steps for more precise selection.

Reference

[1] M.F. Ashby, Y.J.M. Brechet, D. Cebon and L. Salvo, Selection strategies for materials and processes, *Materials and Design*, 25:51–67, 2004.

[2] M.F. Ashby, *Materials selection in mechanical design*, Butterworth-Heinemann, Oxford, UK, 1999.

[3] M.F. Ashby and Y. Brechet, Designing hybrid materials, *Acta Materialia*, 51:5801–21, 2003.

[4] Y. Brechet and J.D. Embury, Architectured materials: expanding materials space, *Scripta Materialia*, 68:1–3, 2013.

[5] F.X. Kromm, J.M. Quenisset, T. Lorriot, R. Harry and H. Wargnier, Definition of a multimaterials design method, *Materials and Design*, 28:2641–6, 2007.

[6] H. Wargnier, G. Castillo, M. Danis and Y. Brechet, Study of the compatibility between criteria in a set of materials requirements. Application to a machine tool frame, *Materials and Design*,31:732–40, 2010.

[7] S. Giaccobi, F.X. Kromm, H. Wargnier and M. Danis, Filtration in materials selection and multi-materials design, *Materials and Design*, 31–4:1842–7, 2010.

[8] P.M. Weaver and M.F. Ashby, The optimal selection of material and section-shape, *Journal of Engineering Design*, 7(2):129–50, 1996.

[9] D. Pasini, Shape transformers for materials and shape selection of lightweight beams, *Materials and Design*, 28(7):2071-9, 2007.

[10] L. Laszczyk, Homogenization and topological optimization of architectured panels, PhD thesis, Grenoble University, 2011.

[11] J.W.C. Dunlop and P. Fratzl, Multilevel architectures in natural materials, *Scripta Materialia*, 68:8–12, 2013.

[12] P. Bollen, N. Quievy, I. Huynen, C. Bailly, C. Detrembleur, J.M. Thomassine and T. Pardoen, Multifunctional architecture materials for electromagnetic absorption, *Scripta Materialia*, 68:50–54, 2013.

[13] J. Mottram, R. Taylor, Thermal transport properties, *International encyclopedia of composites*, 5, pp.476–496, 1991.

[14] P. Leite, Optimal design of architectured sandwich panels for multifunctionnal properties, Ph.D. thesis, DMSM/MAT ONERA, Grenoble, France, 2013.

[15] N. Chakraborti, R. Sreevathsan, R. Jayakanth and B. Bhattacharya, Tailor-made material design:An evolutinary approach using multi-objective genetic algorithms, *Computational Materials Science*, 45:1-7, 2009.

[16] W.A. Khan, J.R. Cuham, M.M. Yovanovich, Modeling of cylindrical pin-fin heat sinks for electronic packaging, *IEEE*, pp. 125–134, 2008.

[17] P. Teertstra, M.M. Yovanovich, J.R. Culham, T. Lemczyk. Analytical forced convection modeling of plate fin heat sinks. *IEEE*, pp. 34–41, 2001.

[18] M. Montemurro, A. Vincenti, P. Vannucci. A two-level procedure for the global optimum design of composite modular structures - application to the design of an aircraft wing. Part 2: numerical aspects and examples, *Journal of Optimization Theory and Applications 155 (1)*, 24–53, 2012.

[19] M. Montemurro. Optimal design of advanced engineering modular systems through a new genetic approach. Ph.D. thesis, UPMC, Paris VI, France, http://tel.archivesouvertes.fr/tel-00955533, 2012.