Optimum design of metal foam in sandwich structures using genetic algorithm

J. Deocon, L. Salvo
GPM2 ENSPG ESA CNRS 5010 BP46 38402 St Martin d'Hères Cédex, France
P. Lemoine, D.Landru, Y. Bréchet
LTPCM UMR CNRS 5614 BP 75 St Martin d'Hères Cédex, France
R. Leriche
LMR CNRS UPRESA 6104, Av de l'Univ., Madrillet, 76800 St Etienne du Rouvray, France

Abstract

This paper presents a methodology based on the genetic algorithm method to optimise sandwich structure. We focus on the interest of such a technique to solve optimisation problems in a non continuous space such as sandwich structures. A case study is presented to illustrate two approaches : one which uses a database of existing face and core materials and the other, more innovative, which optimises the core materials by choosing the optimum density.

1. Introduction

A sandwich structure is a multi-material since several materials are involved : two face-sheets surrounding a core [1,2]. The face materials can be different and are often made of composites or metals while the core is made of cellular materials such as wood, honeycomb (polymeric or metallic) and foams (polymeric and more recently metallic). Each material has a specific function : for instance, in structural applications, the face carries tensile and compressive loads while the core carries transverse load. The main advantages of such a structure rely in its low weight, its high stiffness and considering thermal properties its thermal insulation ability (owing to the foam). The design of sandwich structures requires the determination of the materials (face and core) but also the dimension (thickness of face and core). Concerning the materials, the designer has to choose the materials from an existing database of face materials (generally composite and metals) and core materials (from a foam database for example). However, as pointed out by Gibson [2] there is a more innovative way to design sandwich structures which consist in choosing the constitutive material of the core and then to calculate the required density according to the constraints. This requires knowledge about cellular materials properties as a function of constitutive materials and density [2]. Table 1 summarises the two design routes and the parameters to be determined.

real route	**virtual route**
face material	face material
core material	constitutive material
face thickness	density of the core
core thickness	face thickness
	core thickness

Table 1 : two design routes for sandwich structures

The first method is called the "real" route since it is based on database already existing of materials (foam and core), whereas the second one is called virtual route since the core material defined from the constitutive material and density of the core calculated might not be available from manufacturers. Using the virtual route Gibson and Ashby [2,3] and Bassetti et al [4] have shown that the lightest sandwich beam for a required stiffness in bending can be determined analytically : it means that the core and face thickness as well as the density of the core is fixed and the materials can be choosen since a performance index is obtained (Table 2)

c/l	t/l	ρ_c / ρ_s	Index
$4.3\left[\frac{C_2 B_2}{B_1^2}\frac{P}{b\delta}\left(\frac{\rho_f}{\rho_s}\right)^2\frac{E_s}{E_f^2}\right]^{\frac{1}{5}}$	$0.32\left[\frac{1}{B_1 B_2^2 C_2^2}\left(\frac{P}{b\delta}\right)^3\left(\frac{\rho_s}{\rho_f}\right)^4\frac{1}{E_s^2 E_f}\right]^{\frac{1}{5}}$	$0.59\left[\frac{B_1}{B_2^3 C_2^3}\left(\frac{P}{b\delta}\right)^2\left(\frac{\rho_s}{\rho_f}\right)\frac{E_f}{E_s^2}\right]^{\frac{1}{5}}$	$\left(\frac{E_f E_s^2}{\rho_f \rho_s^4}\right)$

Table 2 : sandwich optimal dimension and performance index

In this table , c is the core thickness, l the length of the beam, t the face thickness, B1,B2 are constants in relation to boundary limit, C2 is a constant , P is the load, d the deflection, b the width of the beam. E is the Young's modulus, ρ the density with the subscript f for the face material, and s for the constitutive material of the core. The performance index for a sandwich structure is presented in table 2 is different from the one for monolithic materials [5] since to minimise the weight for bending beam, both face and constitutive material of the core are important. This clearly indicates that the optimisation of sandwich structure requires a combined optimisation on face material and constitutive material of the core. Table 2 indicates also the optimum dimensions of the sandwich for the requirement, which are fixed by the analysis to obtain the performance index. Strength design can also lead to performance index [4] or can be treated graphically [3] according to the damage mode (core failure, face yield, face wrinkling ...). Ashby et al [3] have shown that it is possible to derive analytical expression of dimension in the case where the density of the core is fixed and the parent core material is the same as the face sheet material. However, the analytical analysis is no longer valid if one consider the real route : the calculations lead to a system of equations which must be solved using numerical analysis. The weak point of such an elegant method is that the performance indices for the sandwich are only valid in the case of one criteria and the only way to deal with several criteria (for example stiffness and strength) is to treat them sequentially. This becomes more and more difficult if the requirements are multiple and not only mechanical : for example if one want to design a refrigerator truck, this requires sandwich plates with mechanical requirement and thermal requirements. Therefore one needs a method to optimise the design of sandwich structure for a complex set of requirements. One simple way is to screen all the possible sandwiches in the real route or virtual route : this requires a lot of calculation since every parameter of table 1 has to be screened but this has the advantage to be exhaustive. To reduce the optimisation time, there are techniques such as gradient methods which are very efficient. However these methods are useful when the optimisation problem is to be performed on continuous variables. This is not the case of sandwich structures in which the determination of the dimension of the structure (face and core thickness) is continuous but the choice of materials is a discrete problem. Discrete problems are well investigated using genetic algorithm and we are know going to describe.

2. Genetic algorithm : application to sandwich structures

The use of genetic algorithm in materials optimisation has been successful in multimaterial selection, such as composites materials [6,7], where the problem is similar :

selection of materials and dimension of the ply in laminate composites. The aim is not to describe in detail the genetic algorithm but to present the main features and to emphasise on its application to sandwich structure selection.

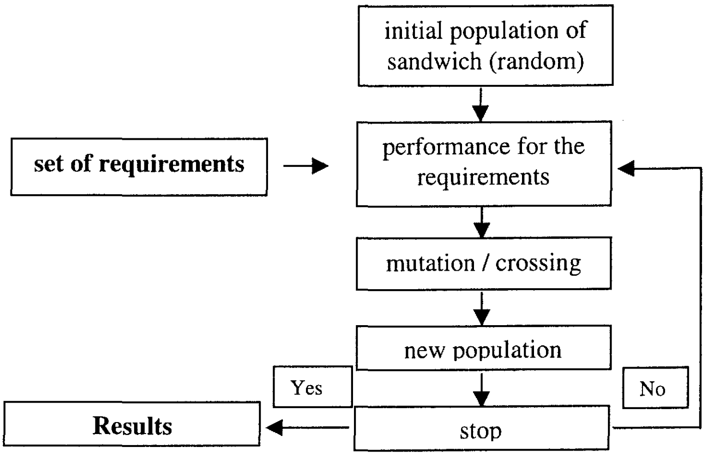

Figure 1 : scheme of genetic algorithm for sandwich selection

The main algorithm is shown in figure 1 : first of all there is the set of requirements which will be used to evaluate the suitability of sandwich to the applications : these requirements can be both mechanical and thermal and in our case we introduced stiffness, strength, thermal insulation of plates and beams. Furthermore criteria for minimising the weight are considered. All these criteria are dealt with a fuzzy way and a global performance of the sandwich is calculated using conventional aggregation [8]. One has to notice that it is not a problem to extend this to buckling or to shells. The second important point is the database : in order to deal with the real route and virtual route described in table 1, we need database of face material, core material and constitutive core material. These database can be specialised for example to aluminium sandwich panels using CES database [9] as it will be shown in the case study.

An important thing to notice before describing the algorithm is that in a genetic algorithm a sandwich structure is coded and this code is used throughout the algorithm. Table 3 indicates the code for a specific sandwich structure in the case of the real route, using a binary system.

	face material	**core material**	**face thickness**	**core thickness**
	Aluminium 6061	Al foam (dens 0.2)	1 mm	20 mm
code	12	35	01010	0010100

Table 3 : sandwich code

Usually genetic algorithm deals with binary code as shown for the coding of dimension, but it has been demonstrated that this restriction to binary coding is not necessary, this is why we used an integer coding for the material : the number refers to the position of the materials in the database. The algorithm presents several subroutines : the initial population, the sandwich evaluation, the population evolution and the ending criteria . The first procedure is to generate randomly a population of sandwiches, coded as mentioned above. The number of sandwiches in this population is an important parameter and was fixed to 100 in our case. The second procedure evaluates the performance of the sandwich to the set of requirements : for each criteria, the sandwich has a mark and a weighted quadratic average from all the criteria is given to the sandwich structure. This procedure allows to classify the 100 sandwich of the population in regard to the set of requirements. This classification is important for the next stage. The population evolution is the important part of the genetic algorithm : the aim of this procedure is to generate a new population from the older one. In order to increase the overall performance, there must be a certain diversity in the population during all the process. To ensure this diversity several procedure are applied to the parent population to obtain children (cf figure 2) :

- cross over procedure : with a choosen probability part of the genetic code is exchanged between two sandwiches to give new sandwiches structure. In our approach we have the possibility to give a different crossing probability for the material part of the code and the dimension part of the code. Usually the probability of crossing is fixed to 0.7 .
- mutation : it means that with a choosen probability a part of its genetic code is modified. In our case we have choose a higher probability of mutation for the material part (0.1) than the dimension part (0.01) in order to explore the whole space of materials.
- among the parent and the children some of them are kept with a probability which is proportional to their performance

crossing			**mutation**		
parent		children	parent		children
1001000100 **1111**010011	⇨	**1111**000100 **1001**010011	1001**0**00100	⇨	1001**1**00100

Figure 2 : crossing and mutation

The last procedure of the algorithm is the criteria indicating the end of the evolution procedure : there are a number of possible criteria but the most often used is the number of generated population : it means that after a number of cycles, fixed by the user, the program is stopped. The last population gives solutions to the problem. The main parameter of the genetic algorithm are :

- size of the population
- probability to keep a sandwich
- crossing probability for dimension variable (thickness)
- mutation probability for dimension variable (thickness)
- crossing probability for materials
- mutation probability for materials

3. Case study

First of all, we have to keep in mind the hypothesis of the approach presented above : the sandwich is made of two materials : one for the face and one for the core. In this case study, we use CES database [9] to built database for sandwich panels or beam as shown in table 4 (some face materials in different metallurgical state, core materials with density and parent core materials of the database are presented). The adhesion between the face and the core is assumed to be perfect : one can notice here that some aluminium sandwich are made by diffusion bonding of the core and the face [10] which gives a good adhesion. In order to stay as close as possible to technological consideration, we have include in the software some restriction on the minimum face thickness and maximum core size.

face materials	core materials (density g/cm3)	parent core materials
2014-T4-T6	Al-Al2O3 Foam (0.261)	A332.0 – A356 – A413.2
2024-T0-T4	Al-TiH2 Foam (0.4-0.5-0.55--0.7-0.8)	S222.1 – S319.0 –
2124-T0	Al-SiC foam (0.071-0.166-0.276-0.415)	S360-S380-S384.1
2618-T4-T6	Al-SiC foam (0.541-0.552)	S390 – S413 – S443
3105-0-H4-H8	Al-SiC foam (0.18-0.2-0.21-0.22-0.26)	2xxx-10Al2O3
5005-0-H4-H6	Al-SiC Foam (0.27-0.351-0.38-0.42-0.5)	6xxx-10Al2O3
5083-0-H2-H4		Al-10SiC(F3K10S)
5154-0-H2-H4		Al-10SiC (F3S10S)
5454-0-H2-H4		2014–2024–3105
6060-T4-T6		5083-5154-5454
6061-T4-T6		6060-6061-6082-7075
7020-T5-T6		Aluminium pure (1-0)
7075-T0-T6		

Table 4 : database of face materials, core materials and parent core materials

To illustrate we have choosen to study the case of a plate of 1 meter square in bending with fuzzy requirements on the stiffness, and strength with the objective of minimising the weight as illustrated in figure 3. For each criteria a mark is given : for example if the weight is lower than 5 kg the mark is 1 and if it is higher than 12kg it is 0. In between the mark is linear with the weight. It is the same philosophy for the other criteria. The analysis using genetic algorithm has been conducted using the real route (with database of existing aluminium foams) and using the virtual route (with the database of parent core foam). Some of the results are presented in table 5 and 6. The restriction on the minimum face thickness was 1mm and on maximum core size 50mm. Only materials with a good average mark on all the criteria are presented.

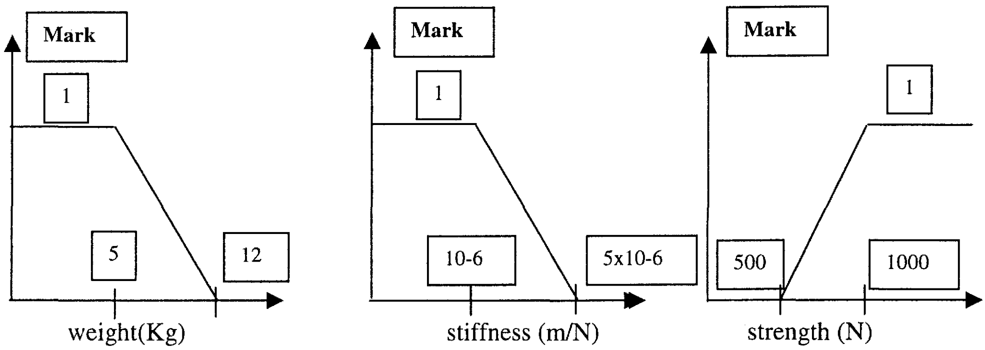

Figure 3 : fuzzy criteria for the case study

face material	core material	face (mm)	core (mm)	weight (Kg)
6062	Al-Al2O3 foam (0.26)	1.04	7	7.5
5454	Al-SiC foam (0.18)	1.05	10.1	7.6
5454	Al-TiH2 foam (0.4)	1.22	7.0	9.36
2024	Al-SiC foam (0.18)	1.01	16.3	9.3

Table 5 : results for the real route

face material	core material	face (mm)	core (mm)	density(g/cm3)	weight (Kg)
5154	Al pure	1.01	7.1	0.16	6.55
5154	A356	1.01	7.1	0.16	6.55
5154	2024	1.02	7.2	0.4	8.7
5154	Al pure	1.29	7.2	0.25	8.7

Table 6 : results for the virtual route

The table 5 and table 6 respectively presents the results for the real route and the virtual route respectively. In any case we will focus on the core since the choice of the face in this case seems not selective. The real route indicates that the metal foam provided by several manufacturers are efficient. However the composites metal foam (Al-SiC and Al-Al2O3) may not be available for low core thickness (below 10 mm) which seems to be possible for Al-TiH2 foam [10]. This was not taken into account in the program. For the virtual route, which means that there is a degree of freedom with the core density, very good results can be obtained providing such a core density can be made by the technique and with such thickness of the core. This shows, as mentioned by [2,3] the great interest of the virtual route. However, there is one doubt about the relationship which give the property of the foam from the parent material properties for such low thickness.

4. Conclusions

In this paper we have presented a methodology to optimise sandwich structure using genetic algorithms. This methodology is suitable to that kind of problem since optimisation occurs in a non continuous space. It has been applied in the case of metal sandwich structures with aluminium foam core for a simple case study (a sandwich plate loaded in bending and for which the aim is to minimise the weight). The results obtained using the real route (based on existing database of foam and face materials) have been compared to those obtained the virtual route (where the parent material core is determined). The structure of the program allows to take into account other mechanical problems such as buckling and even thermo-mechanical problems. This approach is not universal and need to be improved to take into account technological considerations as it has been done for composites materials [8]: for example thickness of the core available with the common manufacturing techniques (in relation to the cells size), density of the core according to the processing route.

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