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# Implémentation d'une procédure d'identification inverse basée sur la toolbox Abaqus2Matlab : Application aux cellules auxétiques

Y. HERSI<sup>a</sup>, A. AYADI<sup>b,\*</sup>, M. MIGHIS<sup>b</sup> and A-M. AYADI<sup>a</sup>

- a. Materials Engineering Department, National Engineering School of Sfax, Univ. Sfax, Tunisia
- b. Centre for Materials and Processes, IMT Nord Europe, Institut Mines-Télécom, Univ. Lille, 59000 Lille, France

Corresponding author: [abderrahmane.ayadi@imt-nord-europe.fr](mailto:abderrahmane.ayadi@imt-nord-europe.fr)

## Résumé :

*Les structures cellulaires en forme de nids d'abeilles auxétiques sont caractérisées par des coefficients de Poisson négatifs. Ces structures offrent des propriétés intéressantes telles que la résistance à l'indentation, la résistance au cisaillement et une aptitude à absorber de l'énergie mécanique sous choc. L'optimisation de telles structures peut conduire à des solutions de conception innovantes. Dans le cadre de cette étude, l'intérêt est porté sur l'optimisation de la forme de cellules unitaires auxétiques en forme de nids d'abeilles. L'objectif est d'implémenter une procédure d'optimisation qui associe les logiciels Abaqus et Matlab afin de démontrer l'efficacité de la toolbox Abaqus2Matlab. Les résultats numériques obtenus ont été conformes aux résultats analytiques menés sur la base des travaux de Gibson et d'Ashby. La précision des résultats basés sur la procédure d'optimisation implémentée constitue une brique préalable à la conception de structures 2D architecturées.*

## Abstract :

*Cellular structures in the shape of auxetic honeycombs are characterized by negative Poisson's ratios. These structures offer interesting properties such as indentation resistance, shear resistance and an ability to absorb mechanical energy under impact. Optimizing such structures can lead to innovative design solutions. As part of this study, the interest is focused on the shape optimizing of auxetic unit cells in the form of honeycombs. The objective is to implement an optimization procedure which associates Abaqus and Matlab software in order to demonstrate the effectiveness of the Abaqus2Matlab toolbox. The obtained numerical results were consistent with the analytical results conducted on the basis of the work of Gibson and Ashby. The accuracy of results based on the implemented shape optimization procedure constitutes a preliminary brick towards designing architected 2D structures.*

**Key words : Auxetic honeycomb, Abaqus, Matlab, Shape optimization**

# 1 Introduction

Honeycomb unit cells represent one of numerous categories of cellular structures which are characterized by their regular shapes and interesting mechanical performances [1]. For example, tetrahedral, triangular prismatic and square prismatic shapes are considered in the context of alleviating the cores of composite sandwich structures [2,3]. Others shapes such as the reentrant honeycomb ones are known to exhibit counter-intuitive mechanical deformations when submitted to external load as opposed to the behavior of their constitutive bulk material. Where the counter-intuitive behavior is induced by the macro-scale negative Poisson's ratio (NPR) of the unit cell/structure. Such structures featured by NPR are known as auxetic structures. Indeed, Poisson's ratio of a solid material is an intrinsic property which expresses the proportionality between the expansion or shrinkage in the direction of mechanical load and respectively in its transverse directions. Thus, under a unidirectional tensile load an auxetic structure expands in all principle directions including the transverse ones. In literature, auxetics are featured with interesting mechanical characteristics such as indentation resistance, shear resistance and ability to absorb mechanical energy [4]. With the development of digital modeling and simulation tools it is more and more possible to optimize the design of cellular structures. Where the use of optimization tools can lower the design cost, reduce the production wastes and can lead to innovative design solutions. In general, the structural optimization procedures of cellular structures can be classified into size optimization [5], shape optimization [6] and topology optimization [7] methods.

In the current study, a shape optimization approach is implemented and then used to test the efficiency of the toolbox Abaqus2Matlab [8] to calibrate the geometric parameters of reentrant honeycomb unit cells. The study was defined in the context of a graduation project between IMT Nord Europe (France) and the National School of Engineers of Sfax (Tunisia). The aim was to test the potential of the toolbox Abaqus2Matlab to manage the flow work between the commercial software Abaqus as a finite element tool for solving partial differential equations and Matlab as a matrix-based platform for numerical computing. In this context, the considered case of study was focused on the optimization of the angle of a reentrant honey-comb unit cell to meet a target NPR. The obtained numerical results were then confronted to analytical solutions to verify the efficiency of the inverse optimization schema.

## 2 Matlab-based structural optimisation

### 2.1 Shape-based structural optimization

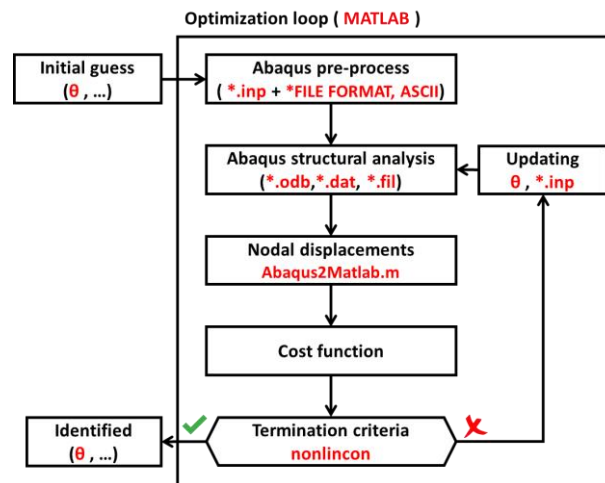
Structural optimization is an iterative process which consists in finding a set of design solutions  $x_i^*$  for independent variables  $x_i$  of a given design  $f(x)$ . Such a process is often reformulated in the form of a minimization (or maximization) process of a cost function  $\varphi(x)$  with respect of the influence of one or more constraints. Based on Abaqus documentation, there exist numerous structural optimization procedures such as topology optimization, shape optimization, sizing optimization and bead optimization. In the context of the current study, the focus is attributed to implementing a shape optimization procedure based on an iterative interaction between Abaqus and Matlab which consists on moving the positions of the nodes defining the reentrant honeycomb unit cell. The design variable is limited to the corner angle of the unit cell. The goal of the optimization is related to minimizing a cost function which defines the gap between the numerical Poisson's ratio  $\nu_{yx}^{num}$  and a target negative Poisson's ratio  $\nu_{yx}^*$ . Despite the simplicity of the size optimization problem, the data exchange workflow between Abaqus input and output and Matlab Optimization environment has long been challenging to establish by non-experts in numerical developing.

## 2.2 Abaqus2Matlab toolbox applied to structural FE analysis

The toolbox Abaqus2Matlab is designed as introduced by *Papazafeiropoulos at al.* to create an interaction between Abaqus as finite element tool for solving partial differential equations in the context of structural mechanics and the computing environment of Matlab [8,9]. Where the toolbox provides access to read and then extract nodal fields stored within the results output data of Abaqus.

The data exchange workflow adopted in the current study (see Fig.1) can be summarized as follows:

- i. Abaqus pre-process with consideration of the initial geometric parameters;
  - a. Generation of input file (\*.inp);
  - b. Adding the command line \*FILE FORMAT, ASCII to generate results in (\*.fil) format;
- ii. Running the Abaqus job;
- iii. Executing the fil2str.m function (provided by the toolbox) to open Abaqus results in a reading only permission;
- iv. Executing Rec101.m function (provided by the toolbox) to extract nodal displacements;
- v. Computing the numerical Poisson's ratio and updating the cost function;
- vi. Verifying the termination criteria;
- vii. Updating the geometric parameters within the initial (\*.inp) file in case the termination criteria are not verified.



**Figure.1.** Illustration of the implemented optimisation workflow

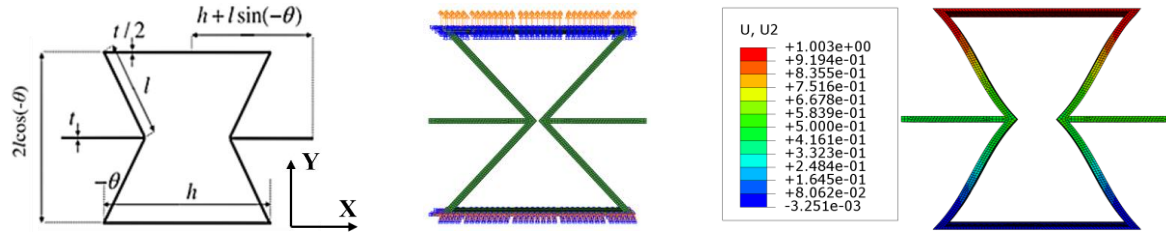
The iterative optimization workflow is ensured by Matlab based on a local optimization algorithm known as sequential quadratic programming (SQP). This choice is mainly justified because of the non-necessity of imposing initial guess variables which must satisfy the constraints of the shape optimization problem as tested by the authors in the following reference [10]. Indeed, the SQP algorithm is called by the Optimization toolbox of Matlab to iteratively minimize a cost function  $\varphi(\mathbf{x})$  of the structural design problem. In this context, the minimization problem is defined as formulated in equation 1:

$$\min_{\mathbf{x} \in \mathbb{R}} [\varphi(\mathbf{x})] \text{ with respect of } \begin{cases} g(\mathbf{x}) \leq 0 \\ h(\mathbf{x}) = 0 \\ x_{lb} \leq x_i \leq x_{ub} \end{cases} \quad (1)$$

Where,  $g$  and  $h$  represent respectively inequality and equality constraints to be respected by the identified solutions  $x_i^*$ .  $x_{lb}$  and  $x_{ub}$  are respectively the lower and upper bounding of the independent solutions.

### 3 Case of study: Re-entrant honeycomb unit cell

The considered case of study was based on the optimization of the angle  $\theta$  of an elementary unit cell. The geometric parameters of the considered structure as well as the boundary conditions and applied load during the FE structural analysis are illustrated in Fig.2.



**Figure.2.** (a) Parameters of the considered re-entrant honeycomb unit cell. (b) Illustration of the considered load and BCs for  $\theta=35^\circ$ . (c) Distribution of displacement components along the Y axis at the end of the FE computation for  $\theta=35^\circ$

#### 3.1 Finite element structural analysis

To evaluate the numerical Poisson's ratio of the chosen auxetic cell, within the framework of Matlab's optimization loop, the numerical pre-processing operations were defined on the basis of Python macros which made it possible to automatically: (i) define the nodal positions, (ii) update the CAD geometry of (iii) update the \*.inp input file and (iv) run the EF job. Indeed, the parametric geometry of the cell was created based on parametric relations of the coordinates of the nodes which define the surface within the (XY) plane and the geometric parameters  $\theta$ ,  $h$ ,  $l$  and  $t$  (Fig.2.a). Moreover, the considered material is introduced elastic styrene-ethylene-butylene-styrene (SEBS) copolymer which is characterized with a Young's modulus of 5.5 MPa and a Poisson's ratio of 0.38. The mesh size was limited to 0.25 mm and the mesh elements were set to the C3D8RH type. A unidirectional virtual tensile test was defined (along the Y axis) where the nodes on the bottom side of the structure were embedded and a displacement of 1 mm was imposed on the opposite side (Fig.2.b). The time of convergence of each EF run was about 5s on a desktop computer equipped with an i7-7700 CPU @ 3.60GHz. After convergence of each calculation, the Poisson's ratio is evaluated in Matlab based on the in plane nodal displacements extracted at the nodes defined on the lateral edges of the side branches of the unit cell.

#### 3.2 Optimisation loop

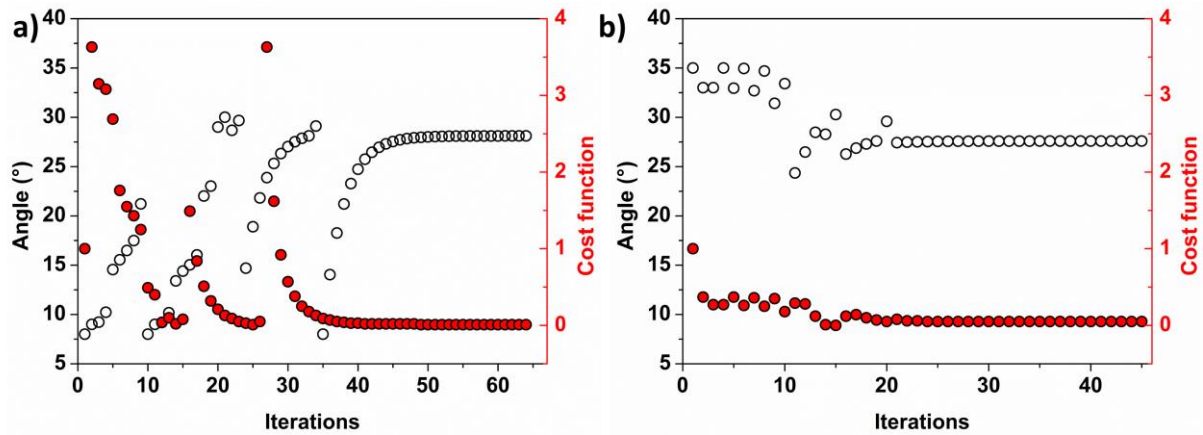
The target Poisson's ratio was fixed at a value of -2, which corresponds to a transverse deformation which is twice the longitudinal one. For reasons of simplicity, the cost function was defined as implicit function of the geometric variable  $\theta_i$  as indicated in Eq. 2. The convergence precisions of Matlab's optimization loop were fixed to  $10^{-2}$  for both  $\varphi$  and the worst case relevant  $\theta_i$ .

$$\varphi(\theta_i) = |v_{yx}^{num} - v_{yx}^*| \text{ where } \theta_i \in [8; 35^\circ] \quad (2)$$

### 4. Results and discussion

The convergence of the shape optimization structural analysis was evaluated by respectively considering the minimum then the maximum extremum values of the angle  $\theta_i \in [8; 35^\circ]$ . The respectively identified angles which satisfied the target Poisson's ratio  $v_{yx}^* = -2$  corresponded to  $28.11^\circ$  and  $27.59^\circ$ . The corresponding time evolution of the cost function as well as the angle convergence iterations are provided in Fig.3.a and Fig3.b. We notice that starting from an initial guess angle of  $8^\circ$ , the cost function

passes through numerous local minima around iterations number 15 and 25 before satisfying the convergence criteria. Such behavior indicates that the used SQP based optimization loop is efficient enough to converge towards global minimum solution. In the other case starting from an initial guess angle of 35°, no local minima altered the convergence towards the global minimum value of the cost function.



**Figure.3.** Evolution of the cost function and unit cell angle as function of the number of iterations for an initial guess angle of 8° (a) and an initial guess angle of 35° (b).

The corresponding numerical Poisson's ratios of the identified angles from the respective optimization operations were of -2.05 and -2.01 respectively. Further verifications (Table.1) were conducted based on the analytical expressions of the Poisson's ratio  $\nu_{yx}$  defined by *Gibson and Ashby* [11] as indicated in Eq.3:

$$\nu_{yx} = -\frac{\varepsilon_x}{\varepsilon_y} = -\left[ \frac{\cos(\theta) * (l * \cos(\theta) + 0.5 * t)}{(h - l * \sin(\theta)) * \sin(\theta)} \right] \quad (3)$$

Where,  $l=13$  mm;  $h=17$  mm and  $t=0.6$  mm.

**Table.1.** Results of the verification operation

Initial $\theta_i$ (°)	Identified $\theta_i$ (°)	$\nu_{yx}^{num}$ (-)	$\nu_{yx}$ (-)	Relative error (%)
8.00	28.11	-2.05	-2.03	0.98
35.00	27.59	-2.01	-2.06	2.43

## 5. Conclusion

The conducted study provides a description of a shape optimization structural analysis based on an interaction between Abaqus and Matlab software via the Abaqus2Matlab toolbox. Based on the implemented workflow it was possible to test the performance of the implemented procedure to identify the angle of a re-entrant honeycomb unit cell by imposing a target negative Poisson's ratio. The used of the SQP based optimization loop was able to identify the global minimum of the cost function. The limited relative errors between the numerical Poisson's ratio and the analytical ones indicate the potential of the toolbox to solve shape optimization structural problems.

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