Extending structural optimization capabilities of FEA softs according to machine learning principles

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Abstract: The purpose of this paper is to extend structural optimization capabilities of some FEA softs (NASTRAN/PATRAN, MARC-MENTAT) by coupling them with MATLAB codes in order to develop light weight design based on machine learning principles. We apply these ideas to some composite material with gyroid structure. The obtained results are interesting from both a theoretical and a practical point of view, shortening the design cycle for this type of materials.

Key Words: structural optimization, finite element simulations, machine learning, composite materials with gyroid structure, stress analysis

1. INTRODUCTION

Two main concepts are used in this paper: design optimisation and machine learning.

Design Optimisation means finding a structural design regarding certain aspects when some structural paramtres of the design vary in some imposed limits previosly defined [5, 12].

The optimisation concept is defined by some constitutive elements [17, 18]:

- **The objective function**. It is a function depending on the structural design parametres and some of the properties of the design object (mass, rigidity, displacements under s specific loads previously defined, stresses). In an optimisation analysis, the objective function shoud be maximized or minimized.

- **Design variables**. These are the structural parameters that are modified to obtain a maximum or minimum objective function locus. Design variables are for example: the thickness of plates, the number of layers of a composite material, the elasticity modulus of a material, or the nature of a material.

- **Constrains of the design variables**. These are the limits between which the design variables can fluctuate in order to mantain the structure in a resonable state. For short the optimisation problem is:

minimize W with the constraints,

$c_j \geq 0$ j=1,...,m

where W is the objective function and c_j are the constraints applied to the design variables.

Usually, in FEA softs the constraints are imposed for stresses, strains, displacements and natural frequencies.

For stresses and strains, the constraints are defined at the element level and for displacements and frequencies the constraints are define at the node level.

The other main concept we take into account is machine learning. The definition of machine learning as in Wikipedia [23] is as follows:

"Machine learning(**ML**) is a field of study in artificial intelligence concerned with the development and study of statistical algorithms that can learn from data and generalize to unseen data, and thus perform tasks without explicit instructions

Machine learning approaches have been applied to many fields including large language models, computer vision, speech recognition, email filtering, agriculture, and medicine, where it is too costly to develop algorithms to perform the needed tasks.

ML is known in its application across to business problems as predictive analytics.

Although not all machine learning is statistically based, computational statistics is an important source of methods in this field.

The mathematical foundations of ML are provided by mathematical optimization (mathematical programming)**"**.

2. EXTENDING FEA SOFT OPTIMIZATION POSSIBILITIES THROUGH MATLAB COUPLING

Design optimization is a progressive process based on some tests in order to obtain a performant object [1, 2, 3, 4, 10, and 11].

In some FEA softs (MARC) the structural optimization searches for:

- An optimum total volume of the material;
- An optimum total mass of the material;
- An optimum of the total cost of the materials.

Marc is orientated on structural analysis and it strongly completes the MSC Nastran optimization solver SOL 200: MSC Nastran solver considers only linear optimization problems while MARC includes some nonlinear aspects [7], [8], [9], [16].

An important feature is the extending opimization capabilities by coupling the opimization module of a FEA soft (MARC) with MATLAB, for example with a DOS command [16]:

"c:\Program   Files\MSC.   Software\Marc\2019.0.0\marc2019\tools\run_marc.bat"   -j Gyro_shear_1_50mm.dat

It starts a MARC solver of the file *Gyro_shear_1_50mm.dat*.

Also the MARC solver admits the option of writing a text file for a node or an element besides the output general file in binary format.
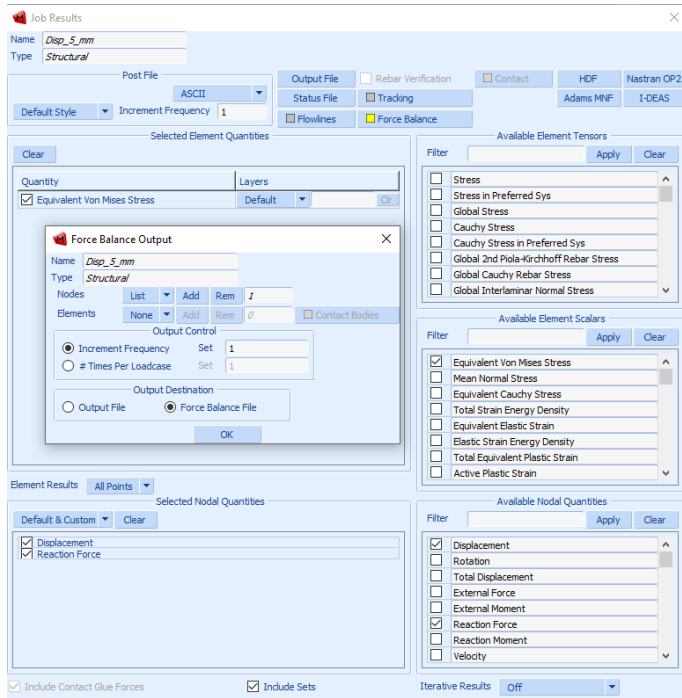
Fig. 1 presents the MARC window.

Fig. 1 The general output window

For example for the settings presented above, one can write a file with the reaction forces in a specified node. The form of the file is presented in figure 2.

Fig. 2 Reaction forces in a specified node

In the input file one can identify a specified variable that is considered a design variable (figure 3).

Fig. 3 Input file

In the above example the thickness of 2D elements (1.25) is identified.

Such files can be easily handled using MATLAB scripts. MATLAB scripts can launch DOS commands (figure 4).

system
Execute operating system command and return output

Syntax

```
status = system(command)
[status,cmdout] = system(command)
[status,cmdout] = system(command,'-echo')
[status,cmdout] = system( __ ,EnvName1,EnvVal1,...,EnvNameN,EnvValN)
```

Fig. 4 Launching DOS commands.

In conclusion, MATLAB scripts can launch a MARC analysis, can modify input files, and can read values from an output file. Also MATLAB scripts can define optimization problems characterized by variables read/written in input/output files of the MARC solver controlled by MATLAB.

## 3. DESIGNING AND CREATING OPTIMAL MATERIALS BASED ON MACHINE LEARNING PRINCIPLES

One optimization problem conected with the machine learning principles explored in this paper is the design and creation of new composite materials with gyroid structure. In this case, during the finite element analysis, modifying some design variables corresponds to a complex geometry change and a single FEA model is not enough.

This is the case of a virtual coupon of a material with a gyroid structure (fig. 5):
- if the design variable is the thickness of the wall of the gyroid, it is very easy to consider it a design variable and to modify it;
- if the design variable is the step of the gyroid, the change from one value to another value implies another FEA model.

Gyroid coupon with a step of 5 mm
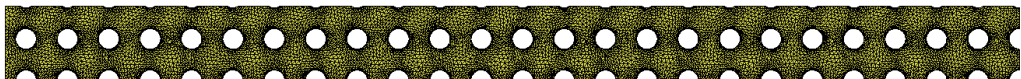
Gyroid coupon with a step of 20 mm

Fig. 5 Different gyroid coupons

A solution to the problem of changing models is to consider a set of virtual or practical experiences. The final objective of these experiments is to define a physical characteristic whose variation we wish to study as a regresion multivariable function depending on some design variables (in this case, the step of the gyroid and the the thickness of the gyroid).

Here we develop a tool for such an optimization problem.

We consider two defining characteristics of the gyroid structure: the mass of the gyroid and the rigidity of the gyroid or the bending deflection.

To compute the mass of the gyroid we create a MATLAB script [6]:

function m=gyro_mass(AX,AY,AZ,h,SizeL,ro,hp)

The main steps of the step are:

-the input data: the dimensions of the coupon (heigh, width, length, the gyroid step, the thickness of the wall equal with the superior and inferior wall, the density of the material);
- the generation of a gyroid structure with the input data as a triangulation structure ;
-the computation of the sum of all the triangles generated ;
- using the thickness of the wall the volume of the structure is determinated;
-using the volume and the density of the material the mass is computed.

The second element of the optimization function is the bending rigidity. To determine this rigidity we used the norm **Standard Test Method for Density of Sandwich Core Materials** [15]. The relations recommended by this norm have an indicative character and will be used to compare in an optimization problems different configurations of some composite materials with gyroid structures (as in fig. 6).
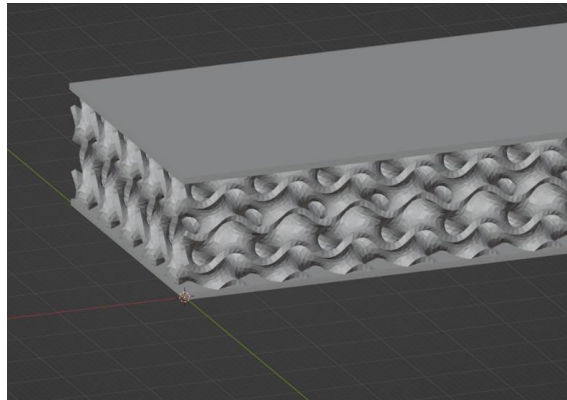

Fig. 6 Composite material with gyroid structure

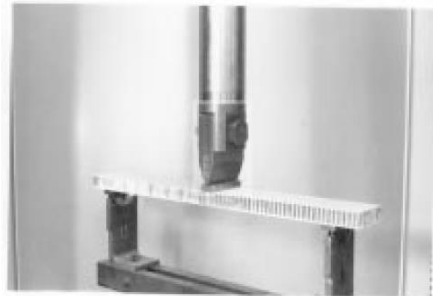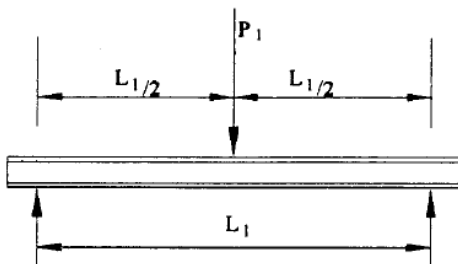We consider the three points bending as presented in figure 7.

Fig. 7 Three points bending

As in [1], the total deflection is:

$$\Delta = \frac{PL^2}{48D} + \frac{PL}{4U},$$

where:

Δ – total deflection [mm]

G – shear modulus of the core [MPa]

E – elasticity modulus of the faces [MPa]

P – applied load [N]

d – the thickness of the sandwich [mm]

c – the thickness of the core [mm]

b – the with of the sandwich [mm]

D – the bending rigidity of the panel [N-mm2]

U – t he sheat rigidity of the panel [N].

U and D are given by the following relations:

$$D = \frac{E(d^2 - c^2)b}{12}, \qquad U = \frac{(d + c)^2 b}{4c}.$$

To compute the deflection with the above relation the only parameter which is not measurable is G, the shear modulus of the core. We determine G for different steps and thick wall configurations according with a ML principle by generating a polynomial regresion depending on two parametres: the step of the gyroid and the thickness of the wall of the gyroid structure. In order to obtain this result we consider a set of virtual coupons modelled as a set of finite element models subjected to shear loads.

The gyroid steps are 5, 10, 15, 20 mm, and the thickneses of the wall are de 1, 1.25, 1.50, 1.75, 2.0 mm. In this way, we created 20 configurations. The values of the FEA models analysis are presented in figures 8, 9, 10, 11.
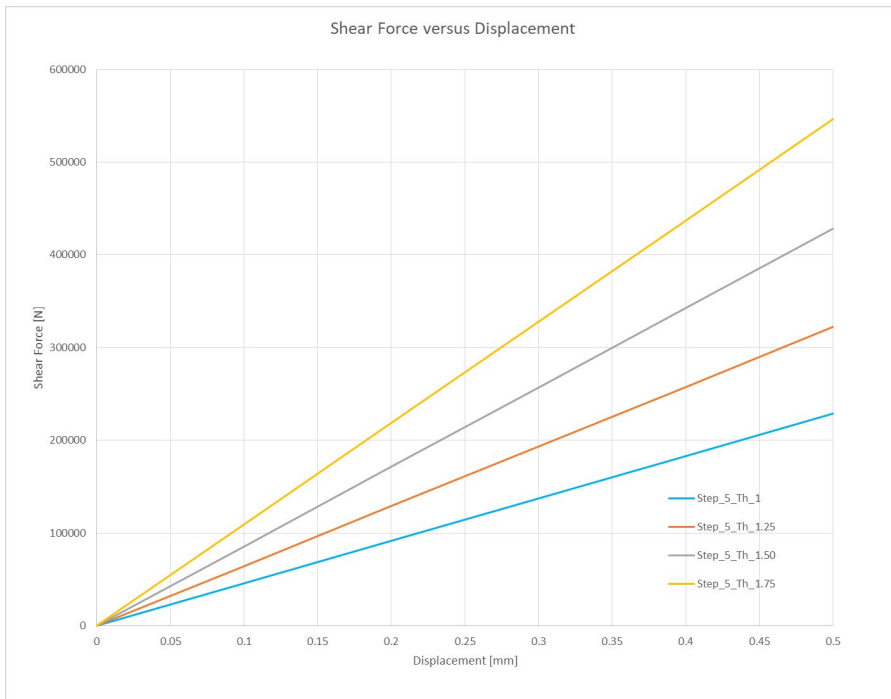

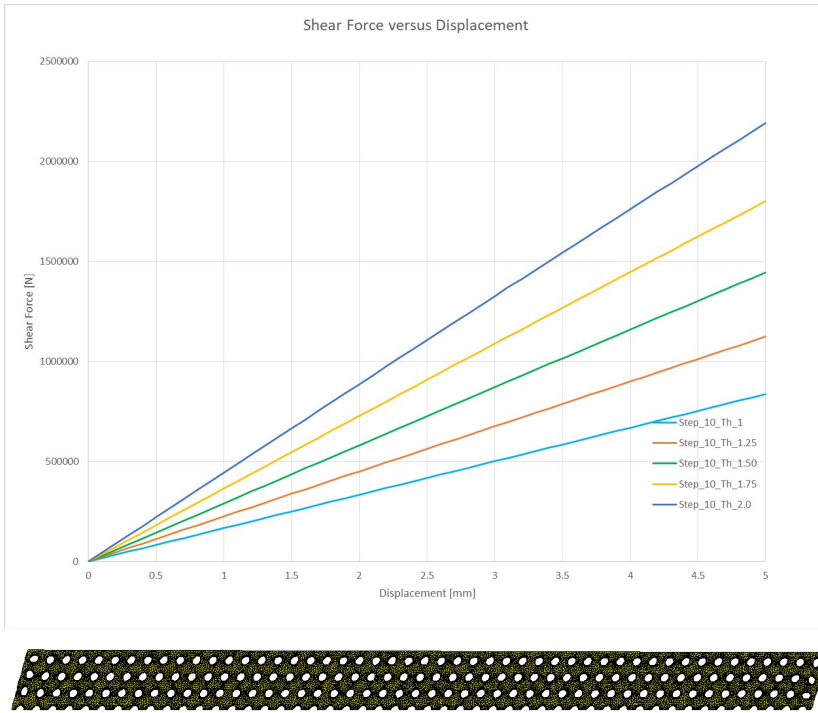Fig. 8 Model with the 5 mm step and the thickness of the wall 1, 1.25, 1.50, 1.75, 2.0mm

Fig. 9 Model with the 10 mm step and the thickness of the wall 1, 1.25, 1.50, 1.75, 2.0mm
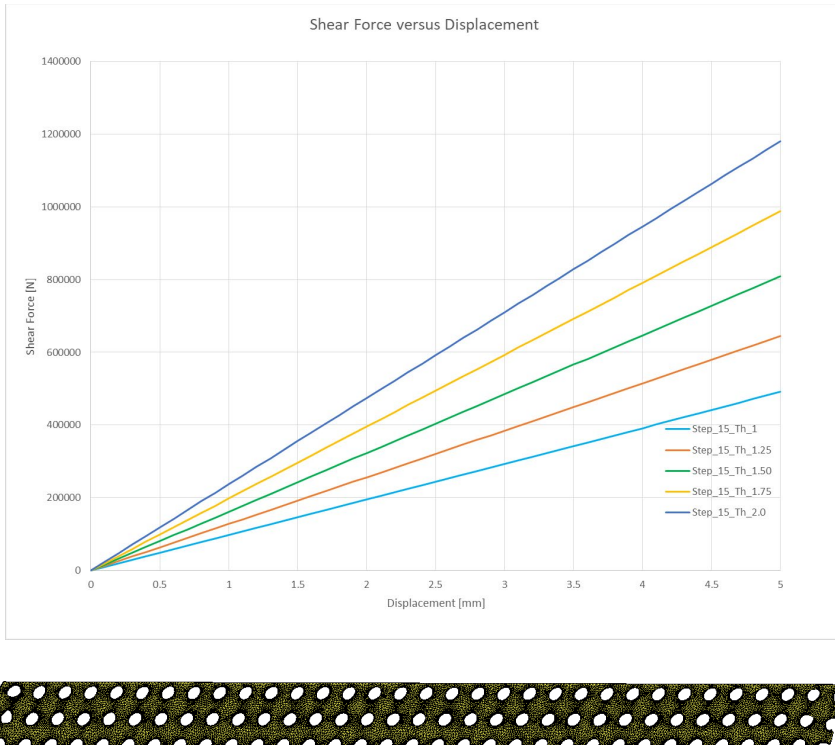

Fig. 10 Model with the 15 mm step and the thickness of the wall 1, 1.25, 1.50, 1.75, 2.0mm
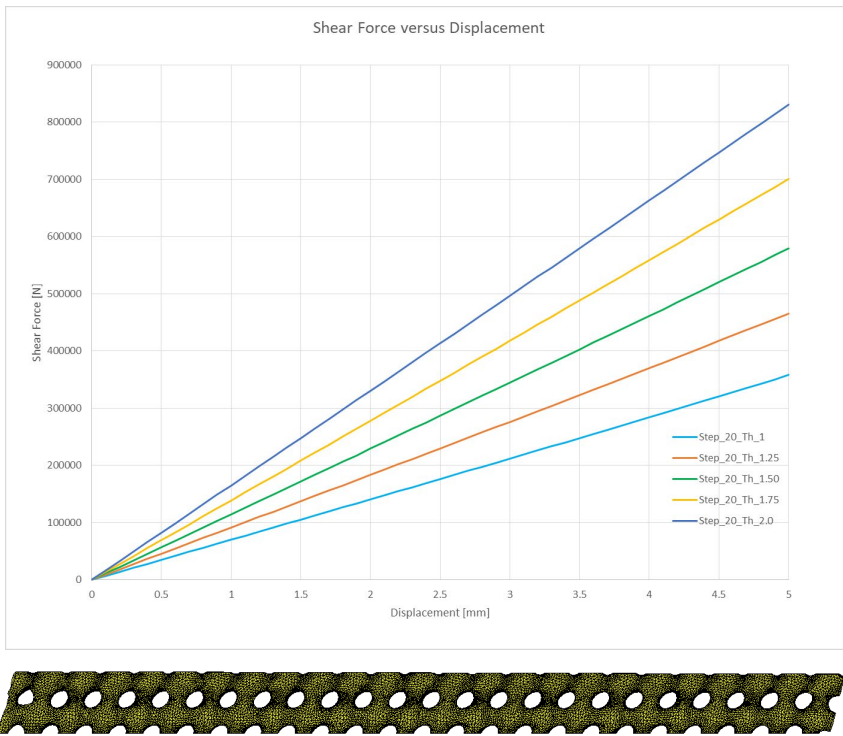
Fig. 11 Model with the 20 mm step and the thickness of the wall 1, 1.25, 1.50, 1.75, 2.0mm

Using these results, for each configuration the shear modulus *G* is (figure 12):

$$G = \frac{\tau_{xy}}{\gamma_{xy}} = \frac{Fl}{A\Delta x}$$
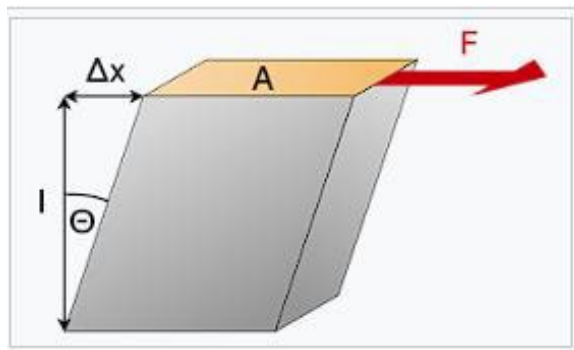

Fig. 12 Elements used to compute the shear modulus G

where:

$\tau_{xy} = \frac{F}{A}$ shear stress,

F –applied force,

A – area where the force is applied,

$\gamma_{xy} = \frac{\Delta x}{l}$ specific strain.

The results are presented in table 1 and in figure 13.

Table 1. The shear modulus G for different configurations

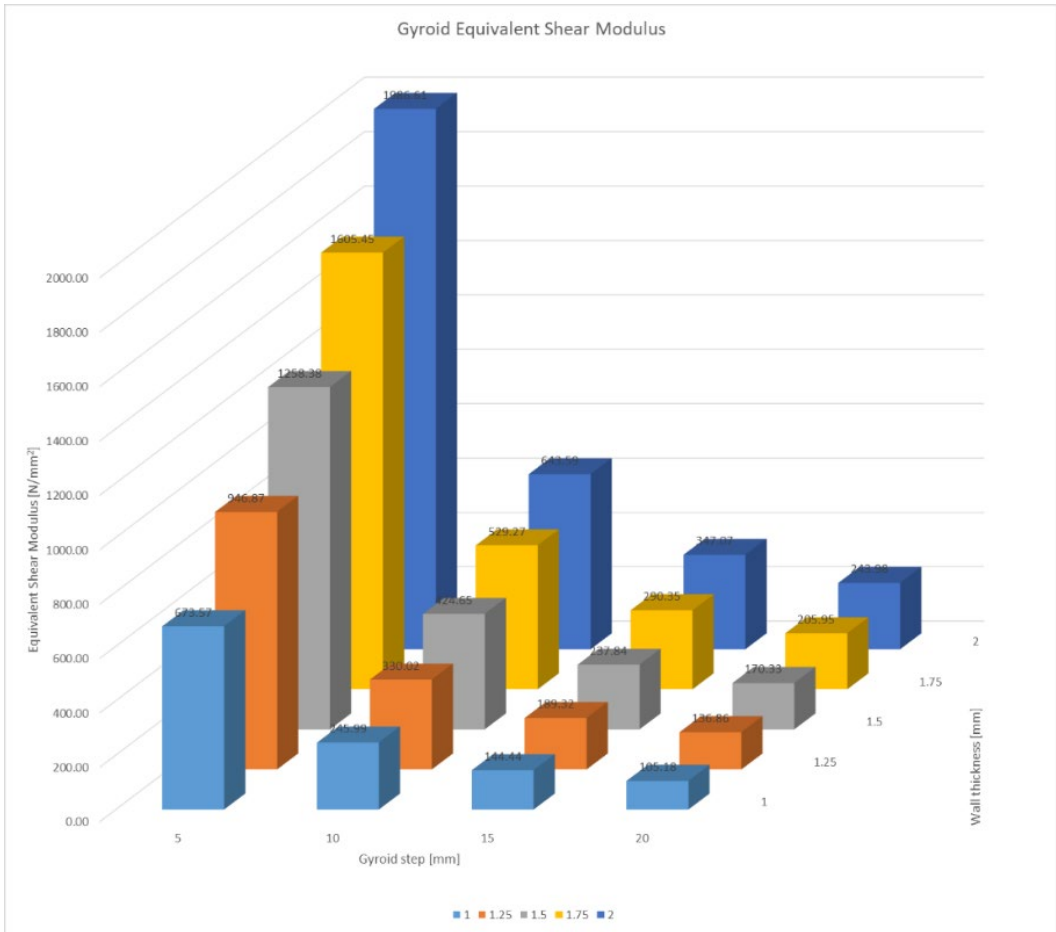| Wall thickness(mm)	Gyroid step (mm)			
	5	10	15	20
1	673.57	245.99	144.44	105.18
1.25	946.87	330.02	189.32	136.86
1.5	1258.38	424.65	237.84	170.33
1.75	1605.45	529.27	290.35	205.95
2	1986.61	643.59	347.07	243.98

Fig. 13 Variation of the shear modulus function of the gyroid step and the thickness of gyroid wall

The next step in building the objective function for the optimization problem is the computation of the multivariable regression function which expresses the shear modulus as a function of the gyroid step and the thickness of the gyroid wall.

A MATLAB script computes the parametres of the multivariable regression [19], [20], [21], [22]. The surface defined by this regression function is presented in figure 14.
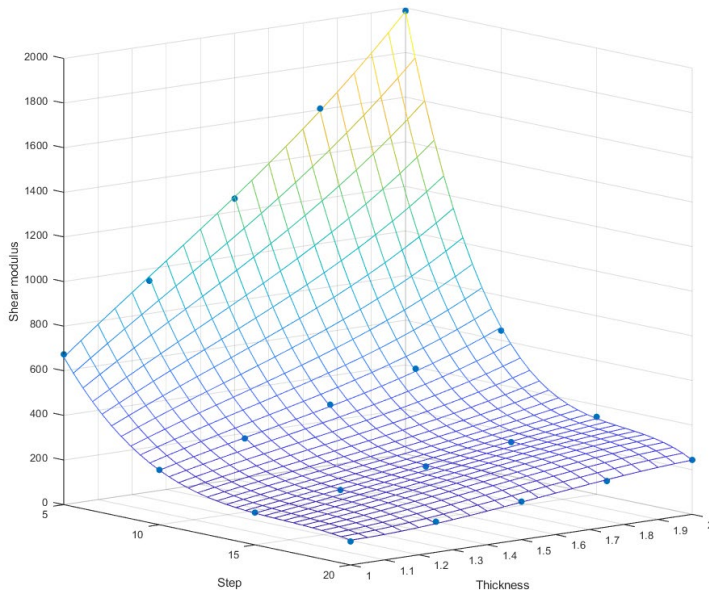
Fig. 14 The surface obtained with the regression function for G

In this way, we may consider that the machine" learned" an empirical dependence:

$$G = G(pas, grosime\ perete)$$

With all these elements we can edit a MATLAB script which computes the shear modulus G for intermediate configurations *function G=shear_reg (step, thickness)*.

4. CONCLUSIONS

In this paper we developed some tools (computing the mass of a compozite gyroid structure, and the shear modulus of that structure) by coupling different FEA softs (MARC-MENTAT) with MATLAB codes. These tools will be used in future optimization problems according to some ML principles [13], [14].

ACKNOLEDGEMENT

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