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Mechanical properties of cookie-shaped auxetics using finite elements in soft robotics application

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Abstract: Auxetic materials, which present a negative Poisson's ratio and, by extension, an inverse deformation mechanism compared to natural materials, are gaining more and more interest. This interest is due to the unusual characteristics presented by which are uncommon to materials find in nature. In this work, through a set of equations, a 4-petal cookie-shaped structure is generated. The generated parametric design is studied with the use of finite element analysis (FEA). Both Poisson's ratio and the stiffness are calculated for every parameter. The minimum value of the Poisson's ratio was found equal to -0.2369 and the stiffness was calculated to have values approximately from 14 to 314 kN/m. After this analysis, as a case study, a grid of the previously generated auxetic structure is placed as an infill of a gripper shaped structure. This application investigates the ability of the structure to hold objects due to its geometry as well as the potentially better distribution of the stresses created within the mesh during the holding process. From the results of the application it is clear that the structure can indeed function as a gripper as well as that the stresses are more evenly distributed along the length of the structure in comparison with another type of auxetic infill.

Keywords: auxetics, metamaterials, Poisson's ratio, soft gripper

1 Introduction

Materials and their systematic study play a significant role in science and technology. Beyond the properties of classical materials, effort is given to create materials with strange properties. These materials are known as metamaterials (from the Greek word meta, meaning „beyond"and the Latin word materia, meaning „matter"or „material").A subcategory of metamaterials are auxetic materials, which were studied for the first time at the beginning of the 20th century by the German physicist Woldemar Voigt Capecchi et al. (2010).

Auxetic materials have a negative Poisson's ratio and, by extension, an inverse deformation mechanism. That is, when a compressive stress is applied to the longitudinal axis, the auxetics contract transversely in contrast to materials with a positive Poisson's ratio, which under corresponding stress expand Bhullar (2015). Auxetics present many unusual characteristics such as synclastic curvature in bending, deformation-dependent permeability, high shear stiffness, indentation resistance, electric permittivity and magnetic permeability, improved damping and sound absorption properties Theocaris et al. (1997), Cho et al. (2019), Stavroulakis (2005), Chinis and Stavroulakis (2023), making them the optimum choice for many applications.

In this work, an attempt is made to study the dependence relationship of the parameters of the cookie-shaped auxetic structure and two of its mechanical properties. In contrast to similar researches Photiou et al. (2021), D'Alessandro et al. (2018), Auricchio et al. (2019), Teng et al. (2022), Xiao et al. (2021), in this, both the Poisson's ratio and the stiffness will be calculated. By calculating these quantities the selection of the appropriate structure can be improved and better respond to the needs of the application. Also, with the completion of this study, the basis for future production of an algorithm that is able to produce the appropriate structure by giving it the desired mechanical properties or vice versa, is set. Also, in this work, the structure that is developed in its final form is used as an infill for a gripper-shaped structure. This structure is similar, shape-wise, to a structure that was presented in a published work about the conceptual design of cellular auxetic systems with passive adaptation to loading Prendergast et al. (2022). In their work, it has been suggested to use an auxetic microstructure with sharp corners that probably can concentrate stresses at these points and due to fatigue, ultimately is more likely to fail Michalski and Strek (2019).

2 Methods

2.1 The cookie-shaped auxetic structure

The first necessary step to carry out the study is the construction of the unit cell of the auxetic structure. This structure was made in Autodesk's CAD software, Inventor, due to the capability of designing parametric equations, parametrizing the design, and importing the values of the parameters from spreadsheets.

The set of parametric equations that produce the structure, as presented in bibliography Xiao et al. (2021), is:

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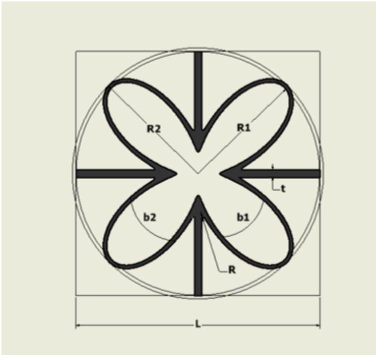

Fig. 1: The cookie-shaped auxetic structure with its variables

$$x(\vartheta) = p(\vartheta)cos(\vartheta - \frac{\pi}{4}),\ y(\vartheta) = p(\vartheta)sin(\vartheta - \frac{\pi}{4}) \tag{1}$$

With

$$p(\vartheta) = \frac{r}{1+b}[1 + bcos(n\vartheta)], \quad and \ \ 0 \le \vartheta \le 2\pi$$

In the above equations, the parameters F_x and F_y are added so that the structure can deform if needed, along the x and y axes respectively. Thus the new equations are as shown below.

$$x(\vartheta) = F_x p(\vartheta)cos(\vartheta - \frac{\pi}{4}),\ y(\vartheta) = F_y p(\vartheta)sin(\vartheta - \frac{\pi}{4}) \tag{2}$$

Obviously, to create a cookie-shaped curve, 5 variables are needed (b, r, n, F_x,F_y). However, in order to create the three-dimensional form of the structure, two curves are needed where one encloses the other. These curves have 3 variables in common (n,F_x,F_y), in particular the variable n always remains constant and equal to 4 since it also defines the number of lobes of the structure. Therefore, after creating the three-dimensional form of the structure, 7 variables are required (b_1,b_2,r_1,r_2,n,F_x,F_y). Next, the members are added through which the structures will be connected to each other and create the grid, these members have a length from edge to edge L and thickness t so two more variables are added. Finally, a last feature is added bringing the total number of variables to 10. This feature is a fillet at the point of connection of the members with the curve and is defined by the variable R. All these are shown in Fig. 1 and at Tab. 1 with their respective default values and the Units of Measurement (UM).

Tab. 1: Variables of the auxetic structure

Variable	r_1	r_2	b_1	b_2	R	F_x	F_y	L	t	n
Value	10.0	10.3	0.70	0.53	0.00	1.00	1.00	200	0.6	4
UM	cm	cm	unitless(ul)	ul	mm	ul	ul	cm	mm	ul

2.2 Finite element analysis (FEA) of the auxetic structure

First, a necessary procedure to start the environment was to define the type of analysis. Due to the geometry of the structure and possible usage of soft material for practical applications, large deformations are expected, therefore the non-linear analysis method was chosen. Also, since the deformation of the structure under static load is studied, the method was specified as non-linear static. Then, with the analysis document successfully created, some dimensions and attributes needed to be defined. Initially, the accuracy of the grid was set equal to 5 mm where for the size of the structure, this value corresponds to a high accuracy (Fine Mesh). With the accuracy determined, it was now possible to produce the mesh. The next necessary step for a successful analysis was the definition of loads and kinematic constraints. The two parallel planes of the rectangular members were used as reference planes. The first plane was set as fixed and at the second plane was uniformly applied a vertical force of 50 N. Finally, aluminum with the characteristics that are presented in Tab. 2 was used in the analysis as the construction material of the structure.

The auxetic structure was studied through the following scenarios:

- Changing the parameter R
- Changing the parameter b_2
- Changing the parameter r_2
- Changing the parameter F_x
- Scaling down the auxetic structure

Tab. 2: Information about the material

Material type	Density	Poisson's ratio	Young's modulus	Failure theory
Isotropic	2685 kg/m^3	0.3	70 GPa	Von Mises

2.3 Prototyping of the gripper

In order to investigate practical applications, the final structure produced will be used as a filler material for a robotic gripper. The gripper and its operation are shown in Fig. 2. Specifically, exerting force on Surface A (Fig 1.a) makes its ends rotate (Fig 1.b) thus creating the holding force. Nevertheless, for a solid structure this rotation, and as a result the holding force, is negligible and therefore a smarter design is necessary. In a related work in the past, a "Re-entrant Honeycomb" type auxetic structure has been applied to increase its performance, with excellent results and improved capability Prendergast et al. (2022). At the same time, this type of auxetic structure is more likely to accumulate stresses at the corners and therefore maybe fatigue overtime Michalski and Strek (2019). As a solution to these problems, the structure designed above is therefore proposed through which there will be a uniform stress distribution due to the absence of corners.

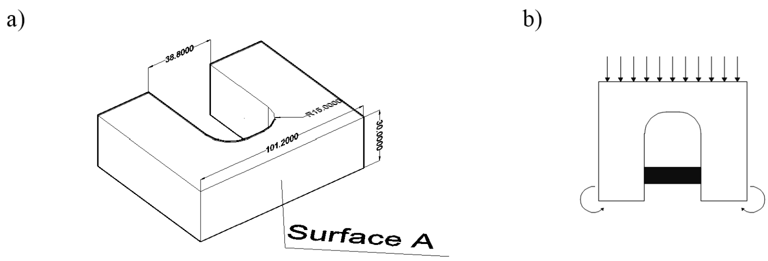

Fig. 2: Definition of the gripper. (a) Three-dimensional drawing of the gripper, (b) Schematic functionality of the gripper

In the next stage, the design of the gripper begins. It is initially designed as a solid structure with a width and height of 83 mm. Next, a shell is created from the previous solid structure with a thickness of 1.5 mm around the perimeter. Finally, the necessary number of cells are placed in the empty space. All this is shown in Fig. 3.

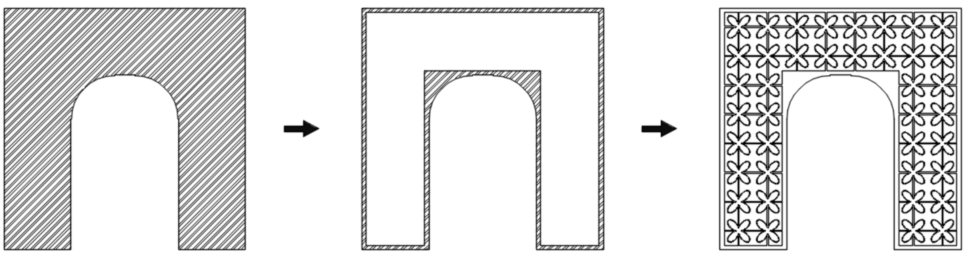

Fig. 3: Design process of the gripper

2.4 Finite element analysis (FEA) of the gripper

The FEA of the gripper was performed in SimScale, a computer-aided engineering software product based on cloud computing. For the analysis a rectangular body was produced simulating the holding object. Due to the existence of two bodies it was necessary to define the contact surfaces between them. The red shaded surfaces was set as rigid (Fig. 4) and thus the kinematic constraints were completed. Finally, a force of 50 N was applied and the material was set to aluminium, similar to that of previous analyses. Having defined all the required data, the simulation was started.

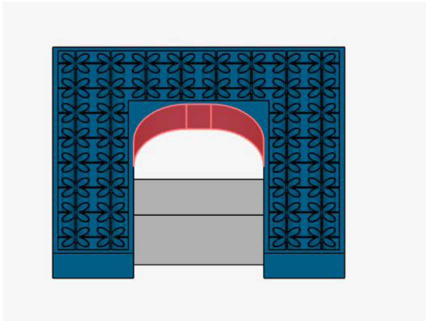

Fig. 4: Kinematic constraints on the gripper

3 Results

In each scenario different values were given to the parameter under study and after FEA the displacements were recorded and thus Poisson's ratio and stiffness were calculated. All scenarios with their results are presented in the graphs below.
From the corresponding graph, the influence of the parameter R on the mechanical properties of the structure is immediately visible. Specifically, for R = 0.2 mm the Poisson's ratio immediately decreased significantly reaching from -0.0859 to -0.1153. At the same time as this reduction, there was a corresponding reduction in the value of stiffness. Then, with each successive increase in the value of the parameter, both the Poisson's ratio and the stiffness increase almost linearly. Finally, for the final value R = 5 mm , the Poisson's ratio of the structure is now positive thus losing its auxetic property.
Then the parameter b_2 is studied. During the first two changes of the parameter, the Poisson's ratio gradually decreases reaching the minimum value equal to -0.0961 for b_2 = 0.5 and remains almost constant until the change of the parameter from 0.56 to 0.59 where it returns to its initial value. In the last change the ratio increases rapidly up to 0.1322 and thus the structure loses the auxetic property again. Contrary to the changing monotonicity of Poisson's ratio, the stiffness decreases continuously reaching from 314845.5997 N/m to 6315.4677 N/m.
In the next study, the first value given to the r_2 parameter resulted in the maximum positive Poisson's ratio and at the same time the minimum stiffness. Subsequently, the second value given resulted in the minimum Poisson's ratio with a value of -0.1619. At the same time, a significant increase in the value of the stiffness is observed. During the following simulations both the Poisson's ratio and the stiffness increase and in particular the Poisson's ratio for $r_2 \geq$ 10.5cm acquires a positive value.
In the scenario of changing the parameter F_x, the values of Poisson's ratio and stiffness are calculated for non-symmetrical structures along y=x and y=-x axes. In this study, Poisson's ratio constantly fluctuates in a small range of values from -0.0966 to -0.1130. The stiffness, on the contrary, decrease with a maximum value of 84397.5869 N/m and a minimum value of 73154.7090 N/m.
The structure up to this point was studied for various parameter values, nevertheless the size of the cell remained constant and equal to 200x200 mm in each simulation. This size is unsuitable for application in a robotic gripper and thus it is necessary to scale it down and test it under the new dimension. The new cell size was set equal to 10x10 mm, i.e. 5% of the original dimension. The values used in this scenario are shown in Tab. 3.

Tab. 3: Values of the parameters used in scaling scenario

Scale	r_1	r_2	b_1	b_2	R	F_x	F_y	L	t	Load (F)
1	10.4 cm	10.7 cm	.84	.67	.20 mm	1.00	1.00	200 mm	.6	50 N
.05	1.04 cm	1.07 cm	.84	.67	.02 mm	1.00	1.00	20 mm	.06	5 N

As show in Fig. 5, Graph "Scale (compared to default value)", when shrinking the structure by 95% the Poisson's ratio increased approximately by 3% from -0.2369 to -0.2284. Similarly, the stiffness for the same change increased approximately by 7% from 28587.7644 N/m to 30890.1300 N/m.
As previously mentioned, the scaled-down structure was used for the robotic gripper. The results of this application are shown in Fig. 6, Fig. 7 and Fig. 8. At Fig. 6 the Von Mises stresses are presented where, as predicted, they are uniformly distributed along the cell. Specifically, the minimum recorded value is 9.427e-4 MPa and the maximum 34.08 MPa. As can be seen in the image, the structure mainly appears to have low stresses while they increase slightly at the corners where the two bodies come into contact. Higher values appear concentrated in the area within the red curve shown in Figure 6, although they rarely exceed 17 MPa. Locally, the maximum values are also shown in the same area. These are shown enlarged and tilted in Fig. 7. Finally, Fig. 8 shows the horizontal displacement of the structure. As can be seen the displacements are almost symmetric, up to numerical errors, along the symmetry axis of the structure, the maximum displacement is at the ends of the gripper with a value of about 3.6e-1 mm. Due to symmetry, one-half of the structure shown in Figure 6 could have been considered. The whole structure is modelled here in order to check the accuracy of the results.

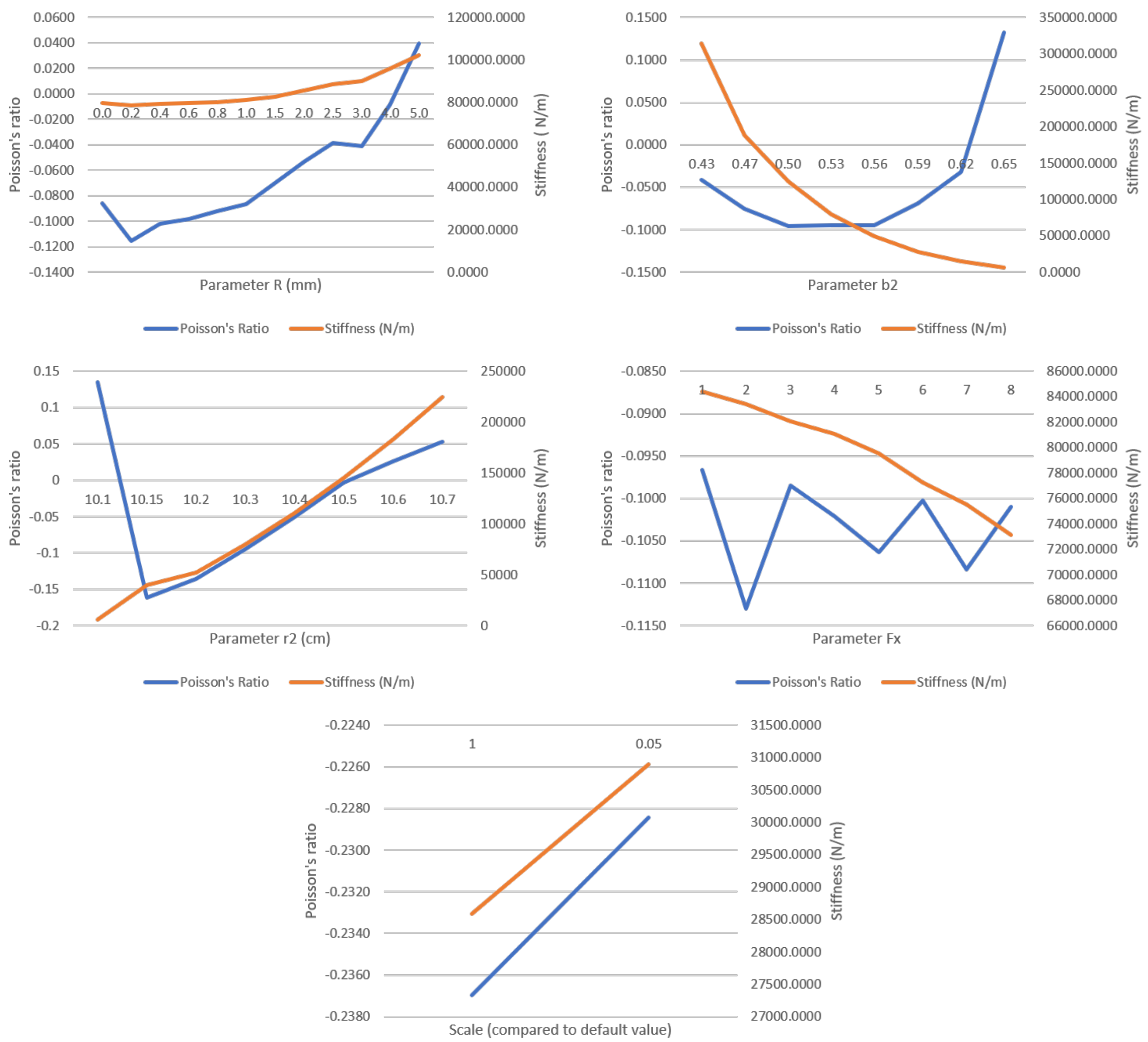

Fig. 5: FEA results of each scenario

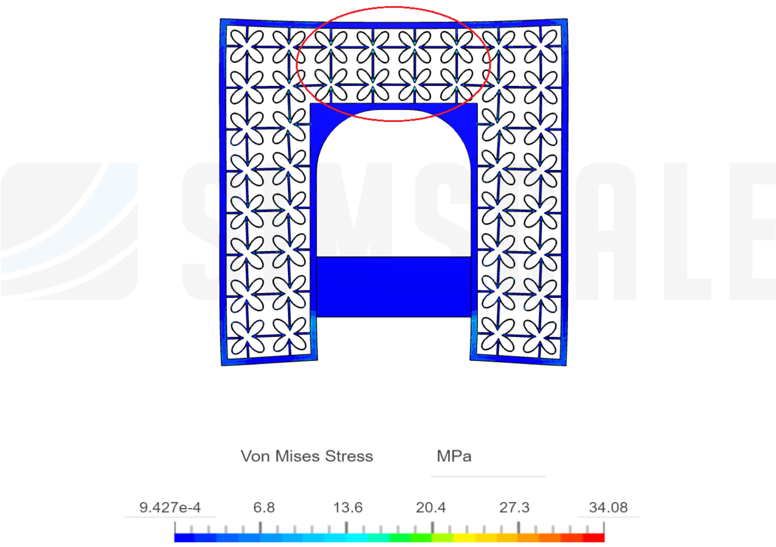

Fig. 6: Von Mises streses of the gripper — Top view

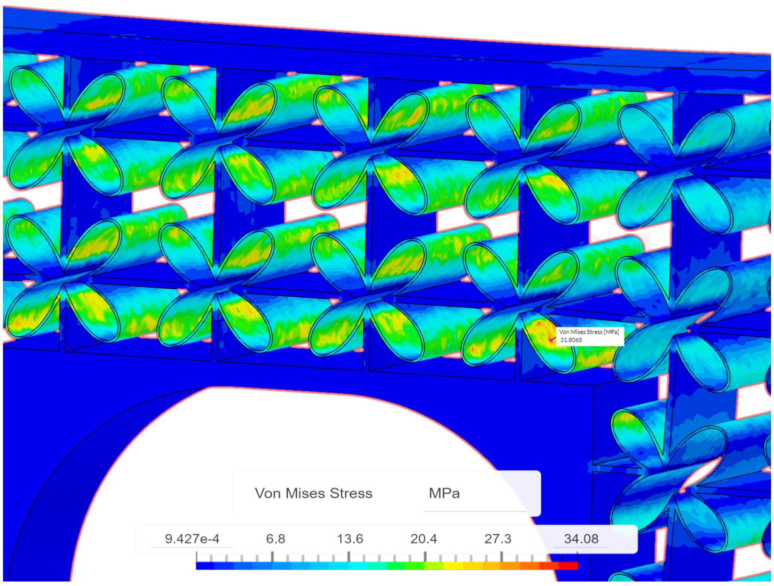

Fig. 7: Von Mises streses of the gripper — Area inside the red ellipse of Fig.6

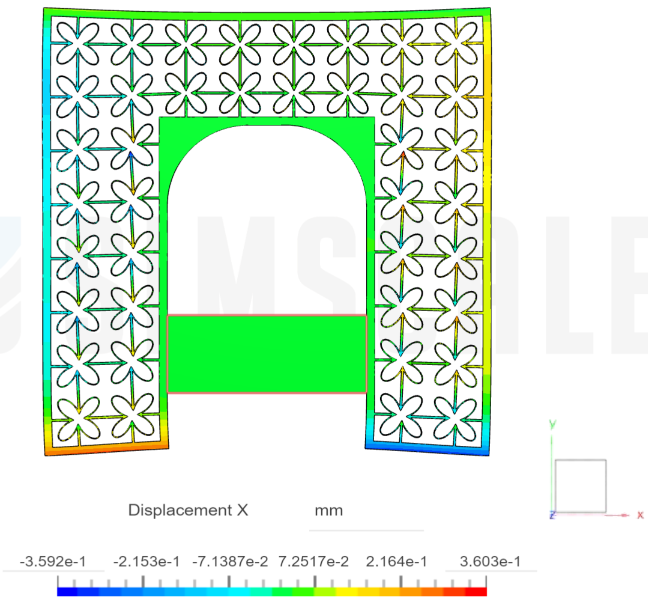

Fig. 8: Displacement of the gripper

4 Discussion and Conclusion

In the present work, both the Poisson's ratio and the stiffness of the cookie-shape auxetic structure ware investigated for the various values of its parameters. As it was seen in the results, the specific structure offers a very wide range of values both for the Poisson's ratio and for the stiffness. For some parameters a more extensive analysis is probably needed and especially in "problematic" points, as for example in the analysis of the parameter r_2 where a rapid drop is observed from the first to the second value of the variable. This range might require a finer discretization of the variable values with more simulations in order to see the true course of the curve. Nonetheless, it is estimated that with a suitable choice of parameters it is possible to design a structure either with a predetermined value of Poisson's ratio, or stiffness, or both at the same time, giving the possibility to cover a large set of applications. In fact, the parametric investigation presented here, can be stored in a database. Subsequently a suitable metamodel or surrogate model can be created in order to predict the mechanical behaviour based on the chosen parameter values or to predict the required design variables from the wished mechanical properties. As for the gripper, although quantitative data was obtained from the finite element analysis, it was not possible to compare it with the corresponding published work as it lacked information necessary to accurately simulate the exact conditions. Nevertheless, from the simulation it was evident that the stresses along the proposed structure were distributed smoother due to the absence of corners. Aside the comparison, the gripper performed as desired given its size and construction material. The grid showed mainly small stresses and satisfactory displacements wherever necessary.

As for future research, the following are suggested:

- Study of the mechanical properties of the structure for different materials.
- Design and study of a three-dimensional cookie-type structure.
- Utilize the database or parametric investigation in order to create a surrogate model for the prediction of mechanical properties for every set of parameter values.
- Development of an algorithm to find the optimal parameters of the structure giving the desired values of Poisson's ratio and stiffness and vice versa.

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