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3D Analysis of Diferent Metamaterial Geometry and Simulation of Metamaterial Usage

This paper investigates the influence of different geometrical structures on new concepts for the formation of technical systems. The ability of some geometric structures to withstand a certain level of deformation, was used to replace joints in certain assemblies of technical systems. Now, all movements are accomplished with deformation of geometrical structures. Obtained results from simulations define the level of deformation which structures can withstand. Designing of 3D models and simulations were conducted in SOLIDWORKS 2016.
Several different structures of metamaterials will be examined. Sixty-four simulations were conducted by changing the internal structure, thickness and orientation of metamaterials. For each simulation, the results were presented as stresses and displacements. Additionally, three model of pliers have been simulated, and its results were compared with the results from previous simulations.

Keywords: *3D model, metamaterial, geometric structure, 3D printing, Solidworks, simulation*

1. INTRODUCTION

The research in the last two decades indicate that modi–fication in the geometric design of internal struc–ture have an effect on the ability of metamaterial to acquire new features that do not exist in their nature. One of the first examples in this field is a specially designed meta–material with a negative light refraction index [1]. This feature is achieved only by changing geometrical form of its structure. Recently, design and production of the new types of metamaterials using 3D technology, as well as their application in various branches in the engineering, has become relatively easy and cheap.

The most popular 3D printers, present on the market today, are FDM (fused deposition modelling) printers. The FDM technology uses a plastic filament that melts in printer nozzle, and extrudes on printing bed to create new part, using the layer by layer system. The 3D printer has become relatively cheap and it open up the opportunity for a huge number of researches in the field of metamaterials. Simply, by altering geometrical structure of metamaterials it is possible to create part with completely new functionality. Using the different types of metamaterials, nowadays, it is possible to produce parts that have movable components without any joints, like door handle and pliers, as it was done in this application [2]. Main advantages of metamaterials are that new functionalities of the parts can be achieved with a smart design of the geometry of its internal structure. In this way some part segments are deliberately weakened and it can be used as an advantage of material properties to elastically deform. In this way it is possible to achieve that some part segments can move relative to each other.

Several groups tested the new types of geometries and their response to external forces in different direc–tions. Bodaghi et al. [3] investigated two different geometries of internal structures using triangles and hexagons, and tested structure response in different directions. Xin Ren et al. [4] moved one step further, and developed three dimensional structure that behave as elastic metamaterial. Bonatti and Mohr [5] created several different geometric 3D structures form spheres and octets and compared results with conventional solid octet-truss lattice. In their work, they used metal 3D printing to create all types of truss lattices with relative density of 20%. Obtained results show that a new struc–ture geometry can increase energy absorption capacity up to 35%, as well as overall strength of metamaterial.

Authors of this paper have a great experience in 3D computer simulation of different mechanisms and mechanical assemblies. Geometrical and mechanical characteristics of deformed balance spring were obta–ined by 3D simulation study using a set of SolidWorks simulations at [6]. Synthesis of bipedal mechanical walker with balancing mechanism has been done in [7], and methodology of preparation for 3D analysis in SolidWorks is presented in [8].

2. PROBLEM FORMULATION

Different shapes of metamaterials can have different responses to external loads. Shapes such as squares, triangles and hexagons were already analysed [2,3].

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These shapes are most in use because they can be combined into different geometrical shapes to fit any surface without gaps. The main idea of this paper is to investigate shapes that cannot fill surfaces completely, or its shape is not regular (Figure1).

The paper presents the regular octagon and irregular octagon (Figure 1b). Irregular octagon is formed by joining of two irregular pentagons [9,10] and repre– sents a basic cell that will be patterned to get desired structure of metamaterial (Figure 1a). As it is shown in Figure 1b, beam members with thickness (T) were used to form basic cells. Sizes of the basic cells were chosen with the aim that they could cover 40x40mm surface, with the whole number of instances. Four different sizes of basic cells were chosen to form meshes of 4x4, 5x5, 8x8 and 10x10 on the surface of 40x40mm, for both types of unit cells (Figure 1).

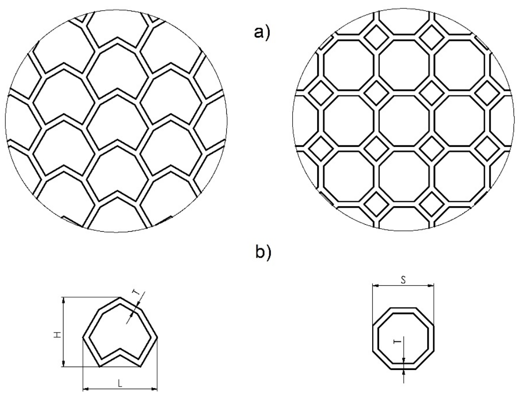

Figure 1. Basic cells of metamaterials and internal structure between two beams

Since joined octagons can't completely cover sur– face, it caused formation of the small rectangles (Figure 1a). Irregular octagons are formed from irregular penta– gons whose shape allows to completely cover given surface (Figure 1a) [9,10]. Each of four unit cells sizes were modelled in four different thicknesses (0.25 mm, 0.5mm, 0.75 mm and 1 mm). The reason why these thicknesses were chosen is because most of low cost FDM 3D printers have nozzle sizes from 0,25 mm up to 1 mm.

Deformation measurement of the entire model can be conducted after covering the square of 40x40mm using unit cells for each type of structure. The model is formed using basic cells located between two parallel beams (Figure 1 and Figure 2). Then, constrains and loads was applied. With the aim to avoid deformation of beams under the load, thickness was much bigger (5x40 mm) than the thickness of the basic cells. Used thick– ness allows the transfer of deformation from external force to internal structure of metamaterial.

As it was said, a model was formed using two beams (5x40mm) and metamaterial structure. Sixty-four diffe– rent combinations were obtained combining two types of metamaterials (regular and irregular octagon), two dif–ferent directions of applied force (Figure 2) and four thicknesses of each structure (from 0.25mm to 1mm).

New structures (Figure 3.) incorporated in the model of plier will be tested through three different simula– tions, since the forces were applied perpendicular on irregular pentagons.

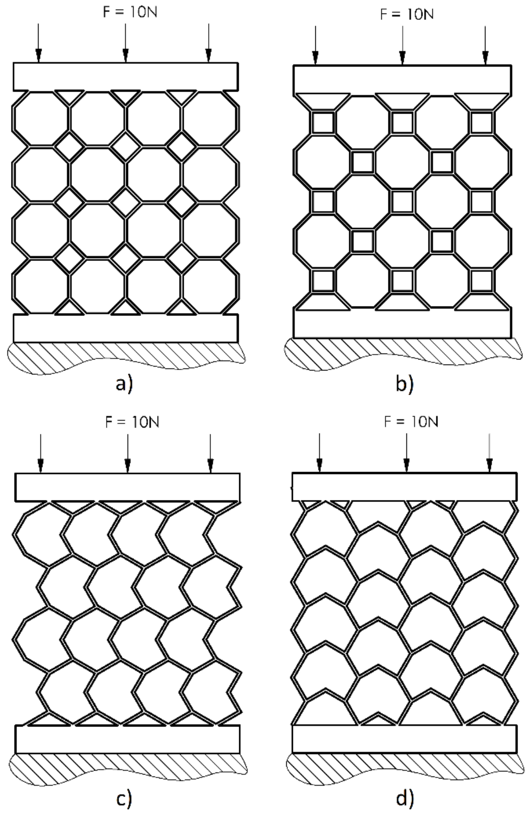

Figure 2. Different types of models for simulation

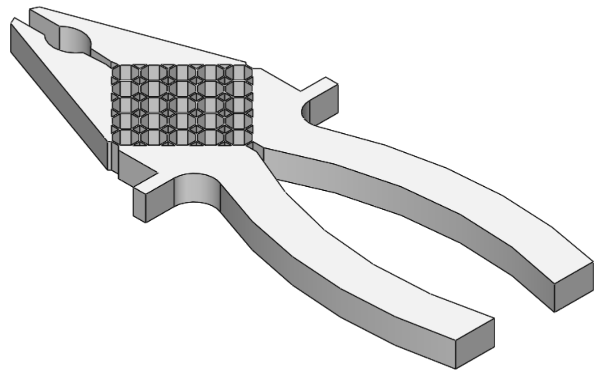

Figure 3. Model of pliers

3. SIMULATION

Mentioned models and simulations were created and carried out in software SolidWorks 2016 (PC confi– guration used for simulations is shown in Table 1.).

The simulations were accomplished with assumption that all material behaviour is linear [6], which means:

-Simulated material compiles with Hooke's law (stress is directly proportional to the strain),

-Models have planar geometry. All simulations were conducted with 2D simplification method for planar stresses,

-Boundary conditions were the same for each model,

-Load was the same for each simulated model (10N) and calculated displacement were observed, with excep- tion of the plier. The pliers simulations were conducted with the aim to make direct contact between handles and to calculate the distance between pliers.

-All stresses will be calculated with Von-Misses hypothesis.

Table 1. PC configuration used for simulations

Processor	Intel(R) Core(TM) i7-7700HQ CPU 3.8 GHz
Installed memory	16GB
System type	64-bit operating system
Operating system	Windows 10 Pro
Application	SolidWorks Educational 2016-2017

The procedure of modelling and simulation was conducted through the next steps:

-16 models, 64 simulations and 3 plier simulations were created and the material ABS was applied with properties given in Table 2,

-Defining 2D static study of simulation for each model. On each model standard fixtures were applied on flat faces, on one of the beams (5x40mm), and on the other, the continuous force of 10N was applied, as it shown in Figure 2. Prescribed displacement was applied on handles of the pliers to achieve contact between them.

-Setting of the mesh parameters was done as it is shown in Table 3.

-Studies of 64 simulations of each of 16 models were done using the same fixtures, load and mesh,

Obtained results of maximum stress and displa–cement from each model were taken for further study, and distance between pliers tips based on simulation was taken for further consideration.

Table 2. Material parameters used for simulations

Material	ABS plastic
Yield strength	30 MPa
Tensile strength	40 MPa
Elastic modulus	2000 MPa
Poisson's ratio	0.3
Mass density	1020 kg/m3

Table 2. Mesh parameters used in simulations

Mesh type	Planar 2D mesh
Mesh used	Standard mesh
Maximum element size	0.7mm
Minimum element size	0.02mm
Mesh quality	High

Used parameters were mentioned in the previous section and obtained results are present as stress, disp–lacement and strain. An example for one of 64 simu–lation prepared in SolidWorks is presented in Figure 4. Also, it can be seen that the orientation of the force is perpendicular to the beam. Command "fixed geometry", from SolidWorks, was used to fix the second beam.

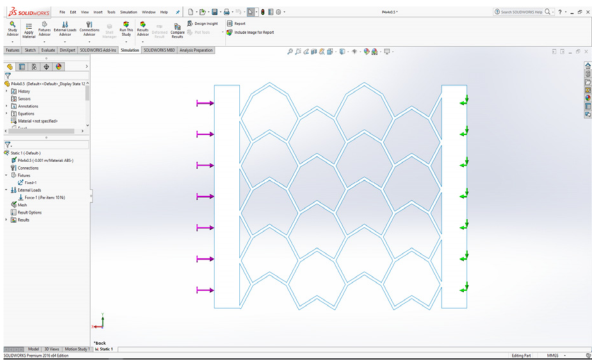

Figure 4. Setup parameters for simulation

4. RESULTS

As it was explained in previous section, parameters for 64 simulations have been established and studies were conducted. The first results are shown in Figure 5, in the form of deformations of different metamaterials presen-ted graphically for regular (orientation 1 – Figure 5a and orientation 2 – Figure 5b) and irregular octagons (orie–ntation 1 – Figure 5c and orientation 2 – Figure 5d).

Four different sizes were considered for the expe–riment on the structures presented in Figure 6. An example for regular octagon in orientation 1 is shown in Figure 6. The structure with 10x10 basic cells can be seen in Figure 6a, 8x8 in Figure 6b, 5x5 in Figure 6c and 4x4 in Figure 6d and they all covered the area of 40x40mm square.

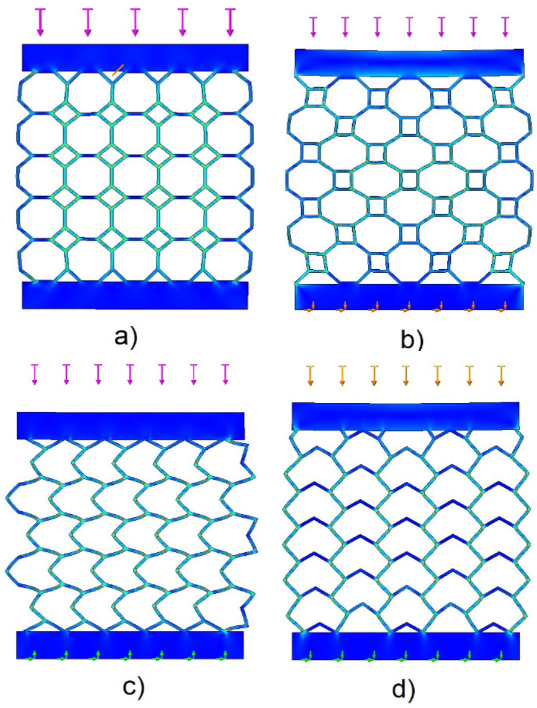

Figure 5. Deformations of different metamaterials

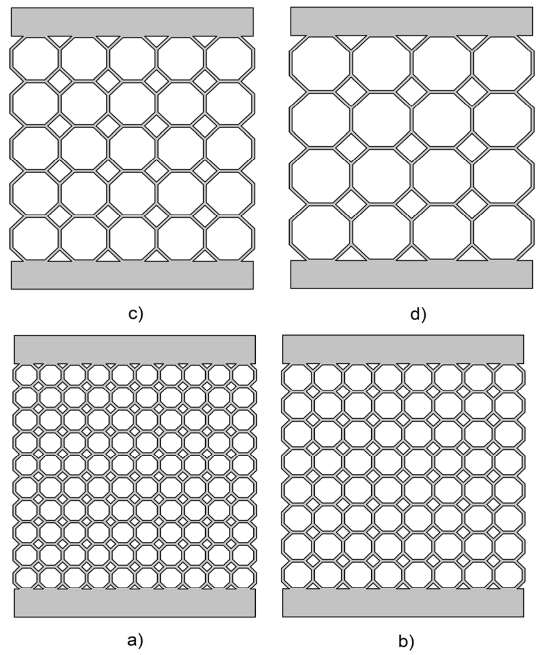

Figure 6. Different sizes of basic cells

The results from all 64 simulations for stresses and displacements, are shown in Table 4. The first column present stresses and the second one displacements. Stresses and displacements for the structure “regular octagon - orientation 1”, is shown in Figure 3a and Figure 6a, for all sizes and thicknesses in Table 4 section 1a and 2a. For regular octagon - orientation 2, results of stress and displacement are shown in section 1b and 2b, for irregular octagon - orientation 1 in 1c and 2c and 1d and 2d showed simulation results for irregular octagon - orientation 2.

In order to compare different structures, the ratio of displacement from the tables was calculated (Table 6). This ratio is calculated for the same thickness and size of basic cells by dividing displacement values of different structures. These results were plotted in 6 diagrams shown on Figure 7.

5. ANALYSIS AND CONCLUSION

The main goal of this paper was to show how different structures can handle the same load (10N) and to find which of these metamaterials will suit best for the used pliers model. As it shown in Table 4, in each of 64 simulations, the highest stresses did not exceed yield strength of ABS plastics, according to the hypotheses stated in section 2. As it was expected from the shape and thickness of given metamaterials, the regular octagon in orientation 1 as shown in Figure 2a, Figure 5a and in Table 4; 1a and 2a is the strongest. The lowest values of strength and highest of deformation has metamaterial with irregular octagon structure and under the orientation 1, as it is shown in Figure 2c and Figure 5c. Values for stresses and displacements are given in Table 4; 1c and 2c. The same behavior can be noted for pliers simulation. The structure with highest deforma– tion also achieved the smallest distance between pliers tips, as it can be seen in Table 5. The smallest defor- mation for regular octagon is in direction 1 (Figure 5a), because direction of the force is collinear with most of structural members geometry. This is also the reason why plier tips with regular octagons in orientation 1 have the lowest amount of displacements (Figure 7a).

From Table 6 and diagrams shown in Figure 6, for displacement-ratio, the biggest difference is between the irregular octagon Io1 and the regular octagon structure Ro1, up to 4.8 times for the thinnest basic cells (0.25)mm. This clearly shows that geometry of metamaterial has significant impact on their characteristics. Diagrams from Figure 6 show that difference in displacement ratios will converge to 1 as thickness and number of basic cell increase. This gives potential for fine tuning of metamaterials mechanical properties such as stiffness and maximal stress. It can be also noted that for every specific application there is a metamaterial, with suitable properties that can be designed.

Simulation for plier also confirms that irregular octagon has highest deformation, as it is shown in Figure 7 and Table 5. Based on these results, it can be noticed that internal structure of metamaterial has the major role in defining the structure stiffness and ability to withstand deformation. With the expansion of 3D printing technology, work like this can be used as a guideline for solving similar problems. The future work will be oriented to the new geometry of metamaterial internal structures and its practical applications.

Table 6. Deformation-ratio

Stress

1a)

Regular octagon orientation 1 - Ro1				
	0.25	0.5	0.75	1
Ro1_10x10	2.41	0.64	0.27	0.18
Ro1_8x8	3.76	0.96	0.43	0.26
Ro1_5x5	10.69	2.62	1.16	0.91
Ro1_4x4	19.61	4.74	2.41	1.36

1b)

Regular octagon orientation 2 - Ro2				
	0.25	0.5	0.75	1
Ro2_10x10	4.12	1.08	0.53	0.39
Ro2_8x8	6.18	1.42	0.68	0.43
Ro2_5x5	14.77	3.56	1.53	0.99
Ro2_4x4	24.06	5.79	3.03	1.78

1c)

Irregular octagon orientation 1 - Io1				
	0.25	0.5	0.75	1
Io1_10x10	5.38	1.22	0.65	0.37
Io1_18x8	8.19	1.90	1.02	0.55
Io1_15x5	20.18	4.84	2.59	1.40
Io1_14x4	29.61	7.01	3.00	1.74

1d)

Irregular octagon orientation 2 - Io2				
	0.25	0.5	0.75	1
Io2_10x10	4.98	1.14	0.66	0.40
Io2_8x8	7.62	1.77	0.97	0.64
Io2_5x5	17.84	4.21	2.12	1.34
Io2_4x4	24.15	5.73	2.52	1.52

Displacement

2a)

Regular octagon orientation 1 - Ro1				
	0.25	0.5	0.75	1
Ro1_10x10	0.0598	0.0116	0.0052	0.0033
Ro1_8x8	0.1150	0.0193	0.0080	0.0047
Ro1_5x5	0.4819	0.0665	0.0237	0.0123
Ro1_4x4	0.9661	0.1278	0.0446	0.0221

2b)

Regular octagon orientation 2 - Ro2				
	0.25	0.5	0.75	1
Ro2_10x10	0.1305	0.0228	0.0086	0.0045
Ro2_8x8	0.2355	0.0397	0.0148	0.0075
Ro2_5x5	0.8766	0.1281	0.0470	0.0234
Ro2_4x4	1.5895	0.2118	0.0781	0.0396

2c)

Irregular octagon orientation 1 - Io1				
	0.25	0.5	0.75	1
Io1_10x10	0.2849	0.0347	0.0111	0.0053
Io1_8x8	0.5516	0.0659	0.0201	0.0091
Io1_5x5	2.1233	0.2524	0.0744	0.0319
Io1_4x4	3.6837	0.4620	0.1354	0.0566

2d)

Irregular octagon orientation 2 - Io2				
	0.25	0.5	0.75	1
Io2_10x10	0.1805	0.0243	0.0084	0.0043
Io2_8x8	0.3456	0.0442	0.0148	0.0071
Io2_5x5	1.2699	0.1557	0.0500	0.0229
Io2_4x4	2.1018	0.2651	0.0808	0.0357

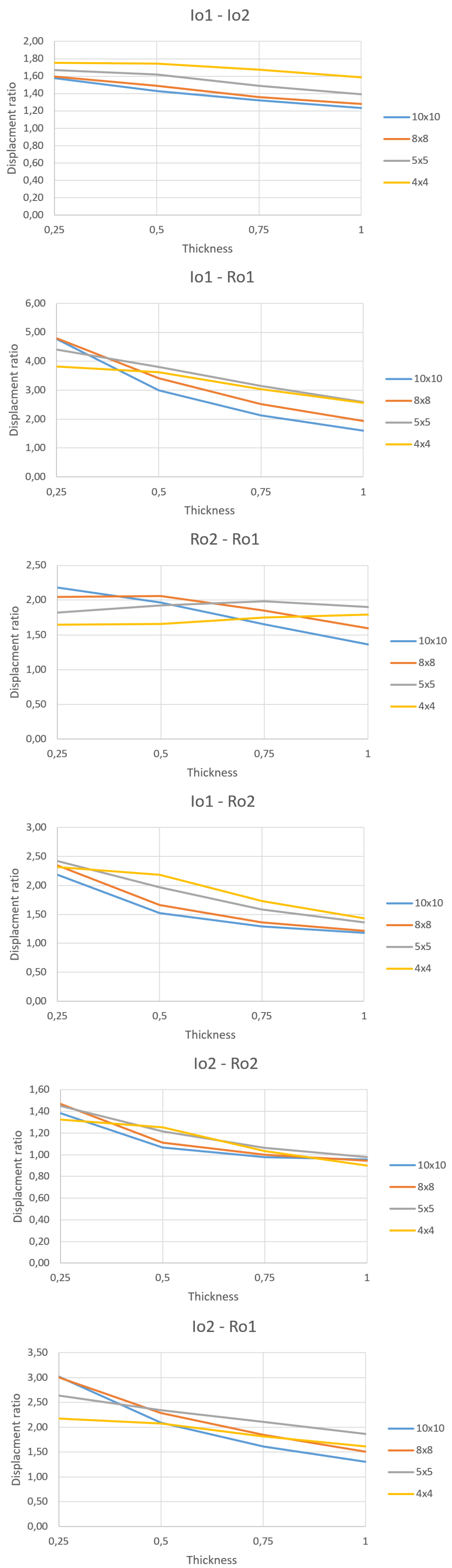

Figure 7. Charts of displacement ratios

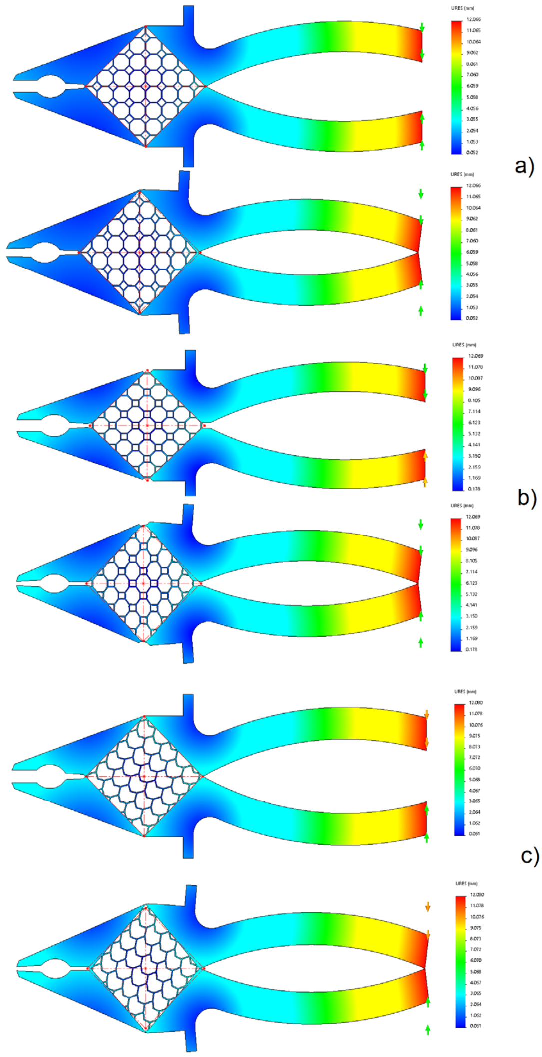

Figure 8 Pliers with different internal structure

Table 5. Plier tip distance

Pliers tip distance	
Non deformed	6mm
Pliers Ro1	3.94mm
Pliers Ro2	1.97mm
Pliers Io1 and Io2	1.18mm

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3Д АНАЛИЗА РАЗЛИЧНЕ ГЕОМЕТРИЈЕ МЕТАМАТЕРИЈАЛА И СИМУЛАЦИЈЕ УПОТРЕБЕ МЕТАМАТЕРИЈАЛА ТАКВИХ ГЕОМЕТРИЈА

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Б. Попконсантиновић, А. Дута, А. Драгићевић

Овај рад истражује утицај различитих геометријских структура на нове концепте формирања техничких система. Способност да неке геометријске структуре буду у стању да издрже одређени ниво деформације, користило се за замену зглобова у одређеним склоповима техничких система. Сада сва та кретања могу да се постигну деформацијом геометријских структура. Добијени резултати из симулација, дефинишу ниво деформације које структуре могу издржати. Пројектовање 3D модела и симулација спроведено је у SoildWorks 2016.

У оквиру овог рада испитано је неколико разли–читих структура метаматеријала. Извршене су 64 симулације променом унутрашње структуре, дебљине и оријентације метаматеријала. За сваки симулацију као резилата су добијани напони и померања. Поред тога, извршена је симулација три модела кљешта, у којима су употребљени мета–материјали испитиване геометрије, а резултати су упоређени са резултатима претходних симулација.