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# Modeling of the Periodic Lattice Structure for Experimental, Numeric and Vibration Analysis

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## Abstract

The paper describes the compression testing of 3D printed plastic lattice structures, the categorization of the selected material by modeling and 3D printing of plastic samples and their testing on a universal machine with a tensile test. Modeling of lattice structures was performed for experimental and numerical analysis as well as additional vibration analysis to optimize the isolation and damping properties of the lattice structure. Numerical analysis using the ANSYS program compares the results obtained by the compression test and the finite element method. Experimental and numerical analysis showed that the shape, i.e. the geometry of the unit cell affects the value of the maximum force, and the vibration analysis showed that in additive manufacturing, the orientation has no significant effect on the vibration parameters except for the modulus of elasticity and that the increase in damping can be achieved by adding external components to the lattice structure in order to improve its ability to absorb vibration energy, such as highly elastic materials, special types of dampers or completely new elements. In the conclusion, the future phases of the research are defined.

**Keywords:** lattice structure; tensile and compressive test; analysis; vibration damping; isolation.

## 1. Classification and application of lattice structures in engineering

Functionally periodic lattice structures are defined as networks of connected solid struts or plates that form the edges and faces of the cell. They are divided into solid two-dimensional (2D) cellular materials (examples are honeycombs) and three-dimensional (3D) cellular structures, which are further divided into 3D open-cell foams and 3D closed-cell foams. They can be stochastic cellular structures (foams) and non-stochastic cellular structures (periodic cellular structures; lattices) as shown in Fig. 1.

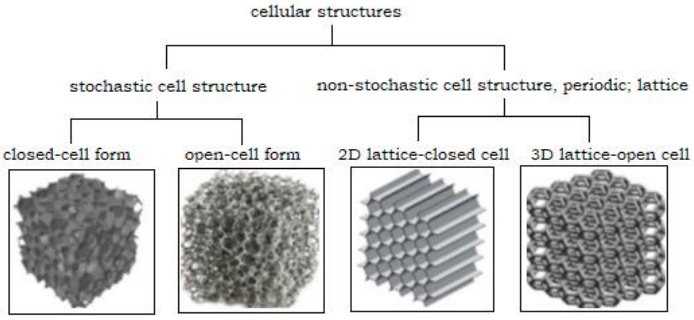


Fig. 1. Classification of cellular structures [1]

Stochastic structures are further divided into foams with open cells and foams with closed cells, while non-stochastic cellular structures or lattices are divided into two-dimensional lattices (with closed cells) and three-dimensional lattices (with open cells). Lattice structures are also defined as topologically determined, three-dimensional open-cell structures composed of one or more repeating unit cells. These cells are defined by certain dimensions and connected by component supporting elements (struts) which are connected by specific nodes [2] [3]. Lattice structures are divided here into 2D and 3D structures, where 2D lattice structures are considered two-dimensional shapes extruded into the third dimension. It is also stated that 3D lattice structures are often found in the literature under the name of strut-based lattices (Fig. 2 left), while there are also triply periodic minimal surfaces (TPMS) (Fig. 2 right) .

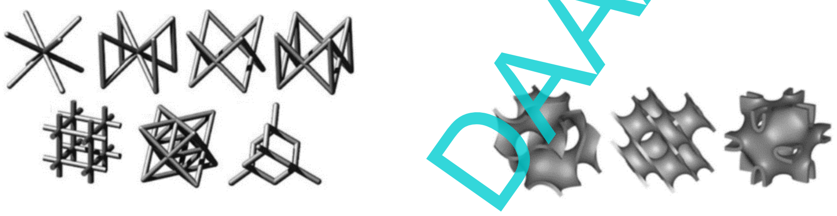


Fig. 2. Structures based on struts; triply periodic minimal surfaces [2]

There are also several more recent divisions of lattice structures: an example is lattice structures divided depending on the arrangement of the unit cell into random and periodic lattice structures. A special subtype of lattice structures is the increasingly common graded (gradient) lattice structure, (Fig. 3).

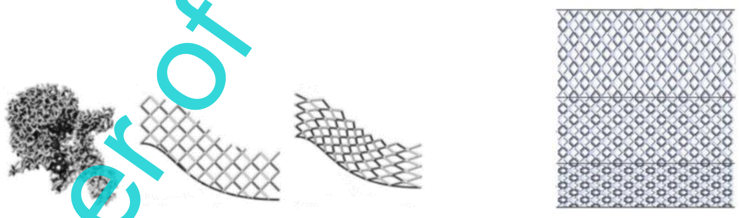


Fig. 3. Random and periodic lattice structures; graded periodic lattice structure [4]

Functionally graded lattice structures are a unique type of lattice structures where the density of the structure is optimally distributed, thus improving the performance of the lattice structure in contrast to uniformly distributed density [5]. Lattice structures have outstanding properties such as lightness, high specific strength and stiffness, energy absorption, high damping and high vibration reduction. Due to their excellent properties, lattice structures have found wide application in the aviation industry, automotive industry, bioengineering as well as other industrial fields. For example, in the field of aviation, not only are excellent mechanical properties expected anymore, but also reduced structural weight. Lattice structures have both biocompatibility and high strength, which can be incorporated into human tissue and bones for the purpose of replacing diseased organs. Lattice structures are particularly widely used in medicine due to their flexible mechanical properties and structural characteristics that can meet specific requirements [4]. The introduction of additive manufacturing in the production of complex cellular structures enabled their wide application in engineering, especially in aircraft structures, automotive parts and engineering medical products. Aircraft components must be strong, but also lightweight, and are usually made of various alloys and ceramics that are very expensive and hardened at ultra-high temperatures. Due to their good strength-to-weight ratio, lattice structures are used in the aerospace industry to improve performance-to-weight ratios that can increase flight efficiency.

## 2. Previous research on periodic lattice structures

Periodic lattice structures as cellular solids have highly efficient energy absorption properties and are suitable for further improvement by designing their fundamental structures. Previous research and studies have classified different groups of trusses based on their topology and which have shown the way to a new strategy to increase their ratio of energy absorption to weight under compression, but also the possibility of optimizing vibration isolation and vibration transmissibility (Fig. 4.). Experimental compression and vibration excitation test results and numerical data obtained from finite element analysis show that a uniform design with an even distribution of relative density provides the highest initial stiffness among all 3D printed lattice architectures [6]. However, a graded design with a rational variation of relative density can significantly increase the stiffness and energy absorption capacity of trusses that are exposed to high compressive stresses as well as vibrational excitation forces. Specific structures in which the relative density of cellular cells varies normally to the direction of the external pressure force can increase the stiffness and energy absorption capacity of cellular solids from 60% to 110% [1]. The possibilities of designing unicellular lattice structures that can combine the properties of light weight and energy absorption by rational variation of porosity within the cellular architecture have also given excellent results after research.

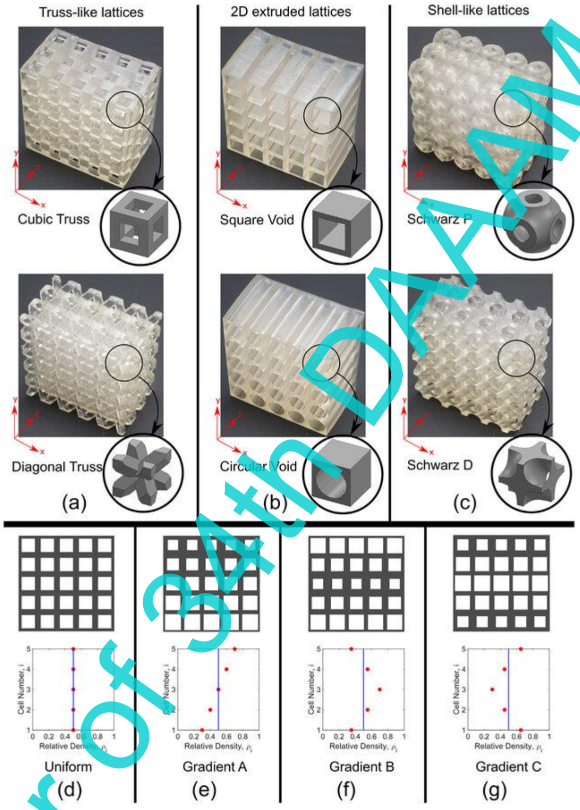


Fig. 4. Different categories of lattice structures with periodic microarchitectures [1].

## 3. Characterization of the material

PLA (polylactide) material was chosen for 3D printing of plastic test tubes for research purposes due to its good mechanical properties, relatively low price, but also because they have not been sufficiently researched. PLA is the optimal choice for prototypes that have special requirements and is by far the most popular material used in FDM/FFF (Fused Deposition Modeling / Fused Filament Fabrication) 3D printing. Since the material properties of the raw material change during the printing process due to a series of parameters (extruder temperature, substrate temperature, air humidity, print speed, age of the material, etc.), it is necessary to strictly adhere to the same parameters in order to be able to achieve reproducibility of the results. In the program SolidWorks 2020, a test tube was modeled for the characterization of PLA material according to the ISO 527-2 standard (Fig. 5.), and printed on a Zortrax M200 Plus printer in .stl format, using the appropriate program Z-Suite (Fig. 6.). Zortrax M200 Plus is a professional FFF printer that is designed for maximum reliability and continuous operation for a long period of time. The working volume of this printer is 200x200x180 mm, and when printing it is important that the model can fit into such a volume.

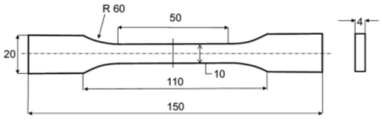


Fig. 5. Standard test sample dimensions according to the ISO 527-2 standard

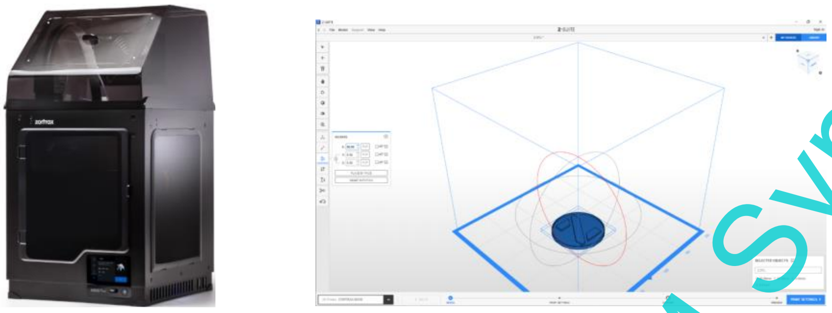


Fig. 6. Zortrax M200 Plus printer; The working environment of the Z-Suite program

In order to enable test reproducibility and determine valid results for subsequent simulation, 5 identical samples (Fig. 7.) are selected for printing and subjected to tensile testing on a universal testing machine with highlighted specifications and the Trapezium X program for test test settings, Fig. 8.

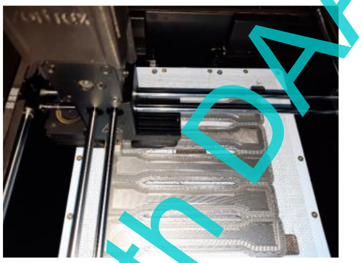
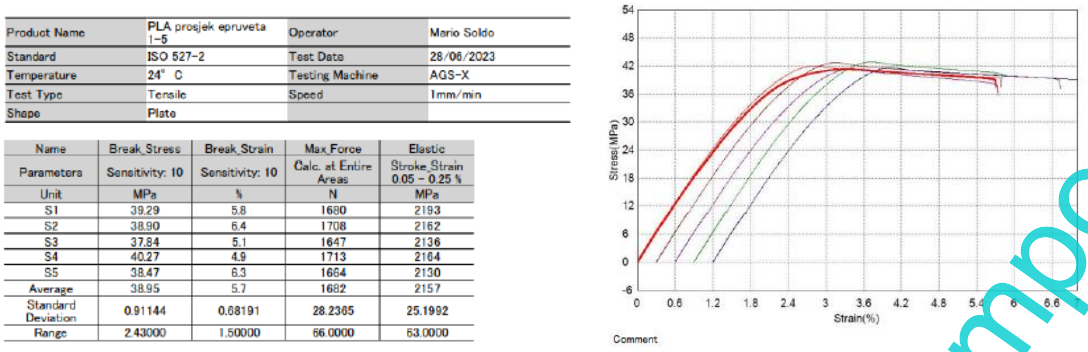


Fig. 7. The process of printing test samples for testing material properties

| SPECIFIKACIJE | |
|---|---|
| Serija | AGS-X |
| Kapacitet | 100 kN |
| Dimenzije | 945(w)x725(d)x2164(h) mm |
| Masa | 525 kg |
| Brzina ispitivanja | 0.001 – 800 mm/min |
| Efektivna dužina pomjeranja | 600 mm |
| Programska podrška | Trapezium X |
| Preporučena temperatura | 5 – 40 °C |
| Preporučena vlažnost | 20 – 80 % |
| Dodatna oprema | Ekstenzometar i pojačalo |

Fig. 8. Universal compressive, tensile, and two- or three-toint tending testing machine with specifications highlighted and Trapezium X test setup program

For the tensile test of the samples, the test parameters of all 5 printed samples were defined and the average of the results was requested. An initial speed of 1 mm/min was selected until a deformation of 0.5% was reached. After reaching a deformation of 0.5%, the speed of the test was 20 mm/min until the test tube broke, which ended the test. After testing all 5 samples, all the necessary data are read from the graphs, which are used for further numerical analysis of lattice structures using the finite element method. The average maximum force was 1,682 N, the modulus of elasticity was 2,157 MPa (between 0.05% and 0.25% deformation), while the average deformation at the break was 5.7%. (Fig. 9.)



| | | | |
|---|---|---|---|
| Product Name | PLA prosjek epruveta 1–5 | Operator | Mario Soldo |
| Standard | ISO 527-2 | Test Date | 28/06/2023 |
| Temperature | 24° C | Testing Machine | AGS-X |
| Test Type | Tensile | Speed | 1mm/min |
| Shape | Plate | | |

| Name | Break_Stress | Break_Strain | Max_Force | Elastic |
|---|---|---|---|---|
| Parameters | Sensitivity: 10 | Sensitivity: 10 | Calc. at Entire Areas | Stroke_Strain 0.05 – 0.25 % |
| Unit | MPa | % | N | MPa |
| S1 | 39.29 | 5.8 | 1680 | 2193 |
| S2 | 38.90 | 6.4 | 1708 | 2162 |
| S3 | 37.84 | 5.1 | 1647 | 2136 |
| S4 | 40.27 | 4.9 | 1713 | 2164 |
| S5 | 38.47 | 6.3 | 1664 | 2130 |
| Average | 38.95 | 5.7 | 1682 | 2157 |
| Standard Deviation | 0.91144 | 0.68191 | 28.2365 | 25.1992 |
| Range | 2.43000 | 1.50000 | 66.0000 | 63.0000 |

Fig. 9. Tensile test settings for testing plastic test samples; tensile test results of 5 PLA test samples for the purpose of material characterization

## 4. Experimental and numerical analysis

There are several software packages for static and dynamic structural numerical simulation, which also include the function of modal analysis of the lattice structure to external vibration excitation, e.g. CATIA, SolidWorks Simulation, ANSYS Workbench, ABAQUS, nTop for control and fine tuning, optimization of the lattice structure with variable thickness and smooth transitions [7]. The most important input parameters for the execution of the simulation are boundary conditions, material addition, coefficient of friction, joining of samples, test speed, mass change, amount of excitation force during vibration testing and, of course, simulation results. It must be noted here that pattern linking is difficult to perform due to the complexity of the functionally graded pattern lattice, and in this case pattern symmetry can be a valuable tool when performing a simulation of the functionally graded lattice structure. The goal of using tools and different simulation methods during experimental testing is to reduce weight, and this is achieved by: choosing materials, consolidating individual cells and their individual parts, and optimizing topology.

### *4.1. Modeling and printing of lattice structure*

To test the behavior of periodic lattice structures, the Simple Cubic sample of unit cells was chosen (because of its simplicity of geometry and accuracy of printing), which is multiplied into a cubic volume (dimensions 50x50x50 mm) using the newly designed Grasshopper algorithm in the program Rhinoceros. The volume of the unit cell is 10x10x10 mm. Multiplication is selected in 3 directions by the same repeating principle (5x5x5), Fig. 10. [8]

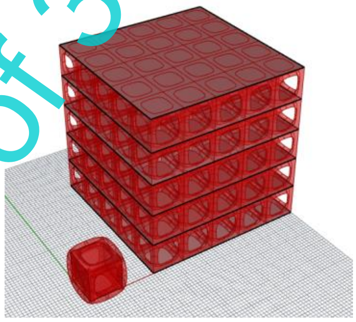


Fig. 10. The final model of the Simple Cubic lattice structure

For the generation process, the Grasshopper algorithm was used to construct samples for compression testing in order to determine the mechanical properties of PLA homogeneous lattice structures obtained by FDM printing. To achieve a relative density of the lattice structure of 0.2, a relative density calculation plugin was inserted and a strut radius of 1.43 mm was selected using the MultiPipe command. After modeling, the model is saved in .step format for loading in the Z-Suite program to generate .stl files that are suitable for loading on a Zortrax 3D printer.

### *4.2. Compression test of lattice structure*

The compression test of the Simple Cubic periodic lattice structure was performed on a Shimatzu universal machine with compression plates in place [9]. The test settings were: test speed 5 mm/min until a traverse movement of 38 mm is achieved; the height or the distance between the plates is 51 mm; the total deformation of the lattice structure is 37 mm (74 %), because by then the lattice structure would have been completely damaged and the phase of thickening of the material would have begun. Out of 6 printed lattice structures, 4 samples with the best print and the closest mass compared to the original model from the Rhinoceros program were selected for testing. The other 2 samples were discarded from further testing due to printing errors (the error is in the discontinuously connected struts between the unit cells. The layer-by-layer collapse of the lattice structure is shown in Fig. 11.

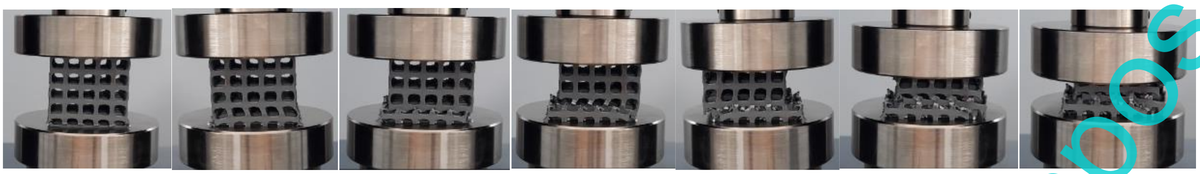
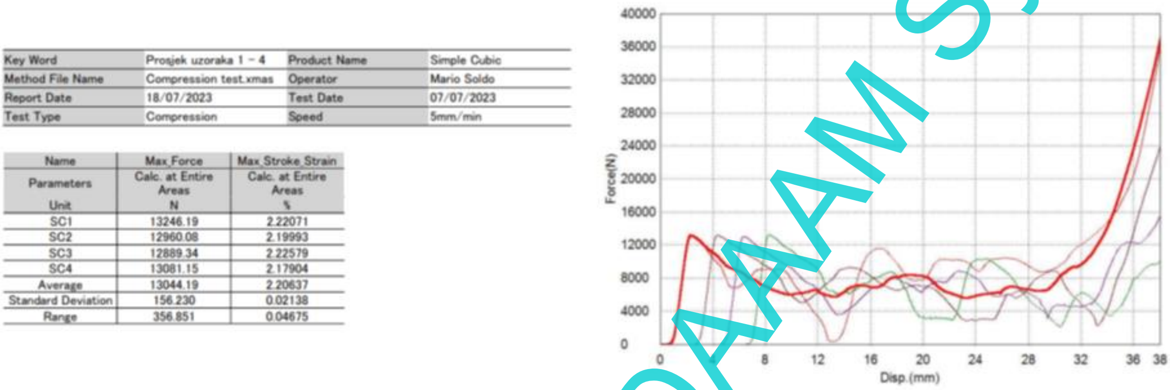


Fig. 11. Collapse of the lattice structure with respect to the increase in the percentage of deformation

The results showed that the maximum force occurs at an average of 1.2 mm of deformation (1 mm is deducted from the results due to idle travel of the traverse) and is 13,044 N (Fig. 12).



| Key Word | Prosjek uzoraka 1 - 4 | Product Name | Simple Cubic |
|---|---|---|---|
| Method File Name | Compression test.xmas | Operator | Mario Soldo |
| Report Date | 18/07/2023 | Test Date | 07/07/2023 |
| Test Type | Compression | Speed | 5mm/min |

| Name | Max_Force | Max_Stroke_Strain |
|---|---|---|
| Parameters | Calc. at Entire Areas | Calc. at Entire Areas |
| Unit | N | % |
| SC1 | 13246.19 | 2.22071 |
| SC2 | 12960.08 | 2.19993 |
| SC3 | 12889.34 | 2.22579 |
| SC4 | 13081.15 | 2.17904 |
| Average | 13044.19 | 2.20637 |
| Standard Deviation | 156.230 | 0.02138 |
| Range | 356.851 | 0.04675 |

Fig. 12. Graphs and average of 4 compression test samples of Simple Cubic periodic lattice structure

### 4.3. Numerical analysis of the lattice structure model

After the experimental analysis, a numerical analysis was performed in the ANSYS program. By entering data in the ANSYS program for numerical analysis using the finite element method, a connection between experimental and numerical results was established. In Engineering Data, the properties of the PLA material according to the tensile test on the tear machine were entered. The difference between the standard PLA material in ANSYS and the selected one is in the Poisson's ratio (previously 0.39) which is set to 0.33 according to scientific papers that investigated the PLA material. Another difference is in Young's modulus of elasticity, which was determined experimentally and was 2,157 MPa. These two values have the greatest influence on the final results of the numerical analysis. In the simulation, boundary conditions were taken: a deformation of 1.2 mm on the upper surface of the sample and a fixed lower surface of the sample Fig. 13.

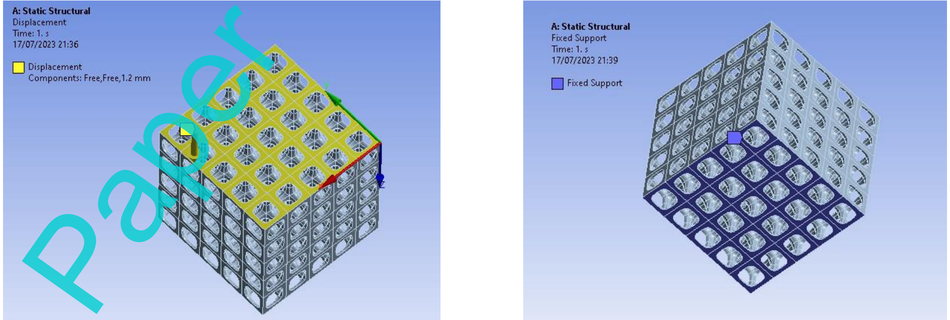


Fig. 13. Simulation boundary conditions: deformation of 1.2 mm on the upper surface of the sample; fixed bottom surface of the sample

The network is generated according to standard settings, and as a result of the simulation, the value of the force that should be applied to the upper surface is selected. In this way, actual compression tests on samples are presented. Numerical analysis concluded that the maximum force (required to deform the Simple Cubic lattice structure by 1.2 mm) is 12,225N. Such simulation settings are accepted as valid for further research since the error of experimental and numerical analysis is within 10%. Experimental and numerical analysis showed that the periodic lattice structure with reduced mass gives higher values of the required force for breaking. Also, it is possible to choose a different shape of the unit cell and achieve the same relative density with the algorithm. Experimental and numerical analysis thus show whether the shape - that is, the geometry of the unit cell affects the value of the maximum force.

## 5. Vibration analysis of lattice structure

The effect of mechanical vibrations is very harmful and leads to a reduction in the life of machine components due to the strength of the vibrations. Isolation is of key importance in reducing and controlling the height of vibration amplitudes. Due to the large influence on the lattice structures and because of the non-uniformity in the structure itself, it is difficult to predict the absorption of vibration energy and the behavior of oscillations, as well as all other mechanical properties of the lattice structures. Various cellular materials have been proposed as good substitutes for providing essential isolation of machinery in order to control vibrations and reduce their effect through energy absorption. The mechanical properties and vibrational behavior of such cell structures can be investigated numerically using the finite element method and experimentally. The assumption is that the unit cell of the structure, which is almost closed in all directions, will have a limited damping capacity. However, the advent of additive manufacturing opens up more opportunities for the development of structures with unique combinations of open, uniform and periodically distributed unit cells, i.e. lattice structures which find wide application in everyday life due to their good ability to dampen oscillation waves and control vibration behavior together with other mechanical properties. Periodic and lattice cell structures have improved vibrational properties compared to solid materials.

As the vibration wave passes through the structure, it is damped based on the topology and geometry of the structure, and the interconnected amplitudes are reduced. By considering design, stiffness and damping properties with proper selection of material type topology and physical parameters, lattice structures can be controlled to achieve the required vibration damping. Fig. 14 shows the vibration damping and isolation through the lattice structure. In this case, the lattice structure can serve as a combination of spring and shock absorber.

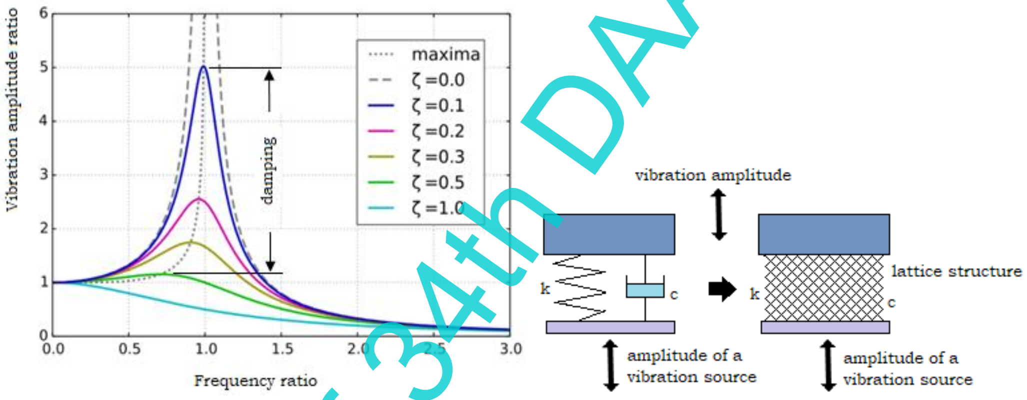


Fig. 14. Damping of vibrations and isolation through a lattice structure

Additive manufacturing offers faster production of complex geometries and savings on wasted material. Lattice structures are preferred over porous materials because they show better application as isolators.

The theory of vibration isolation is based on the excitation force, which is expressed by equation (1):

$$F(t)=F_0\sin(\omega t) \tag{1}$$

where $F_0$ is the excitation force amplitude, $\omega$ is the excitation frequency.

Vibration isolation occurs when the ratio of excitation frequency to natural frequency is $r>\sqrt{2}$. Also, isolation is dependent on damping, i.e. isolation is better when damping is less (see picture above). Therefore, to control and adjust the vibrations of any machine, it is essential to use two main parameters: natural frequency and damping ratio. The natural frequency of an undamped system is denoted by $\omega_n$ and is measured in Hertz (Hz) or the number of oscillations per second. The damped natural frequency $\omega_d$ is the natural frequency of the damped system that determines how quickly the vibrations decrease between two successive bounces and is defined by equation (2):

$$\omega_d=\sqrt{1-\zeta^2}\,\omega_n \tag{2}$$

where $\zeta$ – damping ratio.

Therefore, damping causes the dissipation of the energy of the vibrating system in order to protect it from oscillations and in a certain period of time bring it to stability based on the intensity of the damping coefficient. If the damping ratio is 0 ($\zeta$=0) the machine is not damped, if it is less than 1 ($\zeta$<1) it means that the vibration system is in insufficiently damped operation mode; it is in the critical state when the damping ratio is 1 ($\zeta$=1), and the overdamped mode occurs when the damping ratio is greater than 1 ($\zeta$>1). This means that higher values of the damping ratio indicate that the vibration decreases faster. In addition to the damping ratio, the frequency ratio can show whether the isolator is working properly by checking whether the amount $r>\sqrt{2}$ [10].

The transmission of vibrations is the most common factor on the basis of which the isolation of the vibration system can be evaluated. It refers to the reduction of oscillating force or motion transmitted through the vibration system equipment. In the case of the excitation force, the transmissibility represents the ratio of the amplitude of the force that reached the foundation to the corresponding amplitude of the force that was induced inside the equipment. Displacement transmissibility ($T$) is considered the main parameter for vibration isolation and is defined by equation (3):

$$T = \sqrt{\frac{1+(2\zeta r)^2}{(1-r^2)+(2\zeta r)^2}} \tag{3}$$

where r – frequency ratio [10].

Transmissibility can also be defined as the ratio of the amplitude of the motion that is transmitted to the equipment and the amplitude that was applied in the case of excitation of the motion [11]. Thus, minimal transmissibility is a sign of a good insulator, e.g. only a small value of force or motion can be transmitted through an insulator of minimal transmissibility and vice versa. With this aim, the modeling and management of lattice structures under vibration excitation is one of the best methods for analyzing optimal vibration isolation. Fig. 15 shows the load setting of the vibration system or, in this case, illustrates the vibrations in the vertical direction of the load.

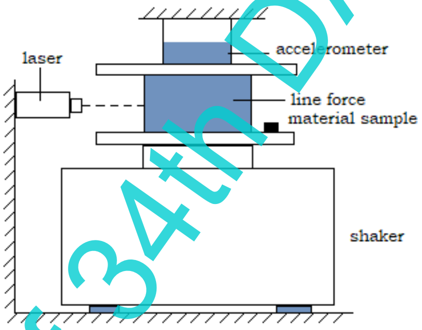


Fig. 15. Device for vibration excitation with appropriate load-vibration in the vertical direction

In this paper, the vibration analysis foresees the examination of the lattice structure under vibration excitation using a vibroplatform with a signal generator, changing different vibration modes of operation that include the own frequency and the isolation frequency of each sample, and it was determined how lattice structures can be used for vibration damping, and by using larger unit cells with with a small volume fraction, the natural frequency can be reduced [12]. Also, the influence of additive manufacturing was determined, which can be an important indicator of damping because the natural frequency, modulus of elasticity and density were compared to production values.

## 6. Conclusion

In this paper, an experimental and numerical analysis was performed and guidelines were given for the vibrational analysis of the Simple Cubic periodic lattice structure obtained by extruding PLA material using the FFF method on the Zortrax M200 Plus printer. Characterization of PLA material was performed on test samples (according to ISO 527-2 standard) obtained according to clearly defined parameters of the print on a Shimadzu AGS-X tear machine and the value of the elastic modulus of 2 157 MPa was obtained in the range of 0.05% to 0.25% deformation. This value was subsequently used for numerical analysis. The next step was to generate a Simple Cubic periodic lattice structure in the Rhinoceros program using the Grasshopper program according to the previously defined algorithm. The models were saved in .stl using the Z-Suite program. The samples were printed according to the previously defined print parameters according to which the test samples were also printed. A compression experiment at a set speed of 5mm/min at 74% deformation determined the maximum force of 13,045 N that was required for the first initial fracture of the sample. It was concluded that this force appears at 1.2 mm of deformation.

After the experimental analysis, a numerical analysis was performed in the ANSYS program. The previously determined parameter of the modulus of elasticity (from testing the test tubes in the tensile experiment) of 2 157 MPa was entered, and Poisson's ratio of 0.33 was added. A deformation of 1.2 mm acts on the upper surface of the model, while the lower surface of the model is fixed. Numerical analysis concluded that the maximum force (required to deform the Simple Cubic lattice structure by 1.2 mm of deformation) is 12,225N. Such simulation settings are accepted as valid for further research since the error of experimental and numerical analysis is within 10%.

Future research that will be based on the conclusions from this paper may refer to changing the diameter of the supports of the Simple Cubic lattice structure in order to reduce the relative density. Experimental and numerical analysis will show whether such a periodic lattice structure with reduced mass can obtain higher values of the required breaking force. Also, it is possible to choose a different shape of the unit cell and achieve the same relative density with the algorithm. In this way, experimental and numerical analysis would show whether the shape - that is, the geometry of the unit cell affects the value of the maximum force. It is also possible to work on changing the multiplication of the sample within the given volume by keeping the mass or relative density and comparing the obtained results. Finally, future research can refer to the incorporation of this algorithm into production processes for the purpose of reducing the total weight of the product and generally improving the mechanical properties of the final product.

After these analyses, a vibration analysis is provided, which includes the modeling and management of lattice structures under vibration excitation as one of the best methods for the analysis of optimal isolation from vibrations. After the vibration analysis, it was concluded that in additive manufacturing, the orientation has no significant effect on the vibration parameters except for the modulus of elasticity. An increase in damping could be achieved by adding external components to the lattice structure to improve its ability to absorb vibration energy, such as highly elastic materials, special types of dampers or completely new elements. Also, the damping properties can be improved based on the manipulation of the 3D printing manufacturing settings. It has not been determined how the topology of the structure affects the damping properties. Therefore, it is recommended that further research be carried out on how to improve the damping effect of graded lattice structures by testing different lattice topologies and changing geometric parameters such as the shape of the cross-sectional surface.

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