# Simulation of the Strength Properties of Lattice Structures, Produced by the Method of Three-dimensional Printing

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**Abstract.** When using three-dimensional printing, parts of the structure are made a lattice. On the one hand, it improves printing performance and reduces material consumption, on the other hand, it confronts the designer with a number of problems in terms of assessing the strength properties of such areas. The authors propose to simulate the properties of the lattice regions precisely using an electronic model and calculate, for example, the Young modulus, in order to use a surrogate solid substitute material for modeling in the future, which simplifies the calculations. As a result, the authors obtained dependencies for calculating the parameters of the substitute material for some types of lattices (square and with holes)

## INTRODUCTION

At present, additive technologies are increasingly being used, among which one of the most accessible is three-dimensional printing by the method of layer-by-layer deposition - Fused deposition modeling (FDM) [1-3]. The question of the mechanical characteristics of the prototypes thus obtained has not been sufficiently studied [4]. We only note that for their full analysis it is necessary to simulate the extrusion of molten plastic and the composite material structure obtained by printing (see Fig. 1) [5].

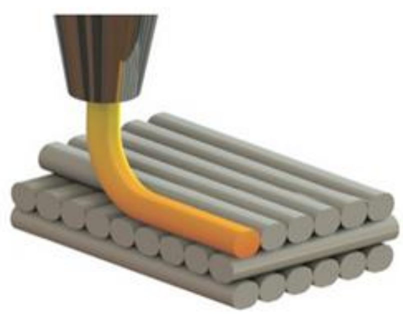


**FIGURE 1.** FDM Printing Material Structure (From https://3dprint.com/wp-content/uploads/2015/02/mat.png)

Often also used are anisotropic models and “worst approximation” models - isotropic with artificially lowered characteristics. Further, when modeling the actual printed material, we will use the latter option.

It is not always wise to print prototypes, pouring the entire volume of the model with plastic in one piece. Numerous cellular structure generators are used (for example, Lattice Commander in Autodesk Netfabb) [6-8]. Obviously, the properties of the lattice regions differ from the properties of continuous material. It is also obvious that modeling the behavior and properties of such gratings under load is directly difficult.

Thus, the problem arises of modeling the properties of lattice regions and taking into account their influence on the strength of the product as a whole in a more productive way than directly modeling the geometry of the cells.

To achieve this goal it is proposed:

- Form a library of surrogate materials equivalent in mechanical properties to lattice structures.
- Identify the main types of gratings.
- Model the properties of gratings by forming a model for strength calculations.
- Parameterize the model to automatically recalculate its geometry and lattice characteristics.

We make several assumptions and simplifications necessary for further exposition:

- Suppose that lattice regions can be considered homogeneous, consisting of some virtual (possibly anisotropic) solid material.
- Suppose that the material of the edges of the lattice is isotropic, obeying Hooke's law.
- In this article, we will consider only the plane (two-dimensional) lattices.

## METHODOLOGY AND MODELING TOOLS

There are several finite element modeling tools that support parametric models and have tools to support numerical experiments. At the time of writing, the authors have a trial version of the Comsol program complex. To conduct an experiment, it is necessary to go through a number of steps, in particular: determine the dimension of the model (2d - flat), set the parameters defining the study, generate a parameterized geometry, select the material of the model components, set the boundary conditions and loads, form a grid, determine the type of analysis (stationary), adjust the solver, carry out the calculation and analyze the results, which is enlarged shown in Fig. 2 [9-11].

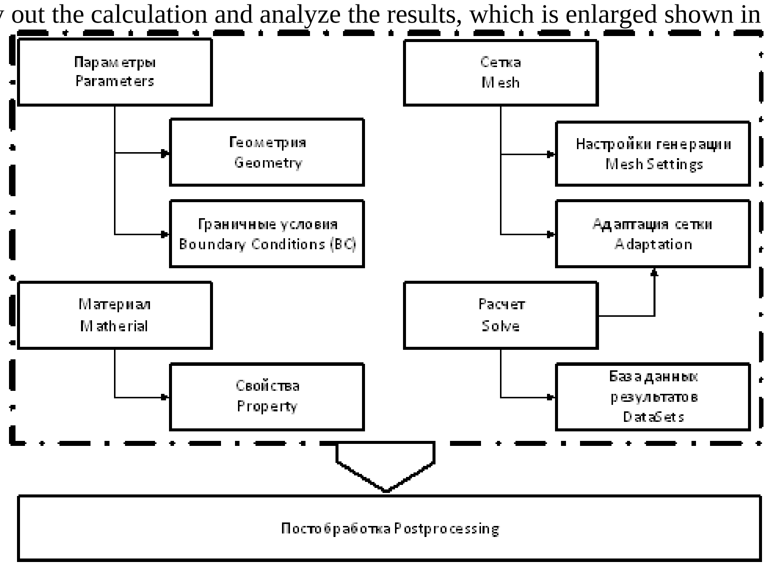



**FIGURE 2.** Parametric modeling properties of the region of the lattice

To calculate the strength characteristics of the lattice region, we model a well-known setup for determining Young's modulus and material strength (Fig. 3) [12, 13].

Two samples of material (a) - homogeneous, b) - lattice, regions 2 and 3, respectively) are placed between the jaws (1).

The left side of the jaws is fixed, the load is applied to the right.

All dimensions of the geometry of the model, the magnitude and angle of application of the load are parameterized. Since the parametric modeling itself is quite obvious, we consider only the parameterization of the lattice (Fig. 4).

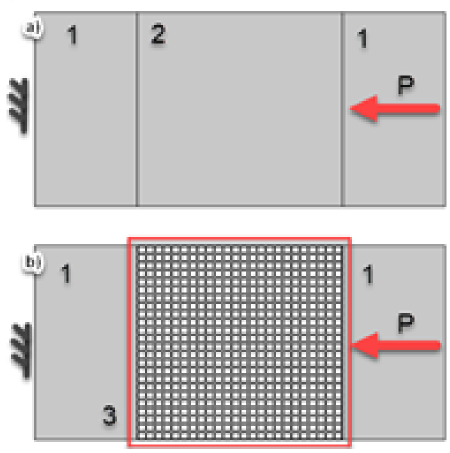



**FIGURE 3.** Scheme of calculations

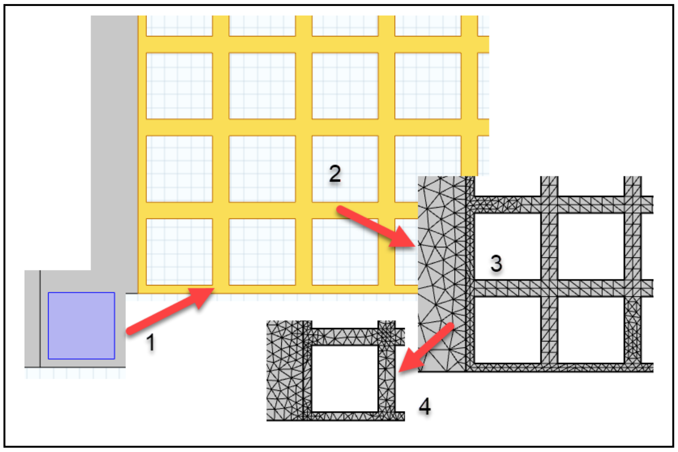



**FIGURE 4.** The formation of the lattice region. 1 - cavity figure, 2 - array, 3 - primary mesh, 4 - adapted mesh

An area of solid material is created.

1. The geometry of a single cavity is created (from the simplest - a rectangle or circle, to complex)
2. The dimensions of the cavity are calculated so as to fill the area of the material a specified number of times with given wall thickness.
3. There is the possibility of transformation of the cavity (for example, its rotation - also in a parameterized way)
4. An array of cavities is formed, which is removed from the region of the material.
5. A primary grid is built, which is further adapted in the necessary areas to clarify the result.

Note that Comsol allows you to automatically change the model parameters to obtain a series of results at the output (Parametric Sweep)

We assume that the main properties of plastic products have the following meanings (as shown in Table 1):

**TABLE 1.** Mechanical characteristics of plastic ABS (according by [14])

| **Параметр/Parameter** | **Значение/Value** |
|---|---|
| Модуль Юнга/Elastic Modulus (MPa) | 2300 |
| Модуль Пуассона/Poisson's ratio | 0.33 |
| Плотность/Density (g/cm3) | 1.04 |

## NUMERICAL MODELLING

We set the following initial parameters: the region of the material is 30x30 mm, and the thickness is 10 mm. Boundary load is compressive, 1000 N by modulus.

The number of cavities horizontally and vertically: 10,15,20,25 (without rotation).

Wall thickness (relative to cavity size): 0.05, 0.1, 0.15, 0.2.

Measured is the horizontal displacement of the loaded (right) side of the sample for a continuous and lattice region.

**TABLE 2.** The relative error in the adaptive refinement of the grid (partially given)

| № | Cells count K | Relative wall thickness t | Relative error err |
|---|---|---|---|
| 1 | 10 | 0.1 | 0.676% |
| 2 | 10 | 0.5 | 0.824% |
| | | … | |
| 11 | 25 | 0.5 | 0.853% |
| 12 | 25 | 0.2 | 1.358% |

Adaptive mesh refinement with a scaling factor of 1.7

We estimate the convergence of the results by analyzing the relative error during grid adaptation (see the appendix). In the parameter variation range, the relative error does not exceed 1.409%, which indicates the good convergence of the results.

Since the cross-sectional dimensions and the load on the lattice and solid sample are the same, we can estimate the change in Young's modulus through the ratio of the displacements of the solid and the main sample, since according to Hooke's law $\Delta l=(PL)/(ES)$, where $\Delta l$ – deformation of material sample, L – is it’s length, P – loading value, S – cross-sectional area, E – Young's modulus.

The displacement of the solid sample is the same and is $\Delta l_1=36.710\ 10^{-3}$ mm. The deformations of the lattice sample are presented in Table 3.

**TABLE 3.** Deformation of the lattice region under load when changing mesh parameters

| Cells count K | Relative wall thickness kwall | Total displacement (mm) |
|---|---|---|
| 10 | 0.1 | 0.187281 |
| 15 | 0.1 | 0.187277 |
| 20 | 0.1 | 0.187281 |
| 25 | 0.1 | 0.187275 |
| 10 | 0.15 | 0.121889 |
| 15 | 0.15 | 0.121874 |
| 20 | 0.15 | 0.121853 |
| 25 | 0.15 | 0.121849 |
| 10 | 0.2 | 0.088729 |
| 15 | 0.2 | 0.088527 |
| 20 | 0.2 | 0.088438 |
| 25 | 0.2 | 0.088359 |

Since, in fact, a solid sample is replaced with a reduced one proportional to the cell wall thickness and since the wall thickness is set relative to the cell size and the cells completely fill the computational domain, it is obvious that the number of cells when the sides of the cavity are parallel to the loading does not affect the displacements (we neglect here the question of cell wall stability). The averaged data are shown in the Table 4 below.

**TABLE 4.** Deformation of the lattice region under load when changing mesh parameters

| Relative wall thickness kwall | Relative deformation dl2/dl1 | The calculated Young's modulus of lattice field MPa |
|---|---|---|
| 0.1 | 5.103 | 450 |
| 0.15 | 3.320 | 692 |

| | | |
|---|---|---|
| 0.2 | 2.412 | 953 |

In a first approximation, the dependence can be considered linear and the decrease in Young's modulus is inversely proportional to the doubled coefficient of wall thickness with respect to the starting material.

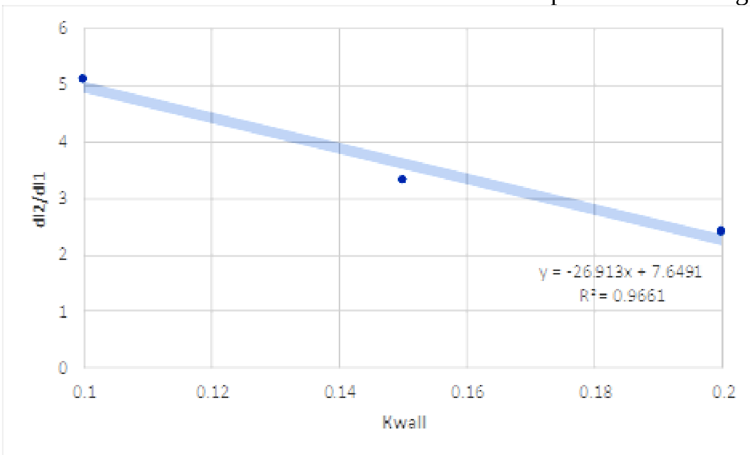



**FIGURE 5.** The dependence of the relative displacements of the samples on the coefficient of wall thickness

On the other hand, the wall thickness coefficient determines the volume of the material left, that is, in fact, the actual cross-sectional area. Thus, in the limit when the wall thickness does not leave a cavity (kwall=0.5 the deformations become equal. At the same time, the larger the cell size and the thinner the wall, the greater the influence of the deflection of the walls in the transverse direction, which explains the deviation of the dependence on a straight line.

Let's consider several grids with more complex geometry.

Firstly, we will perform the calculation under the conditions of the previous problem when the rectangular cavity is rotated by an angle of 0.10 and 20 degrees. See examples of grids in the figure below.

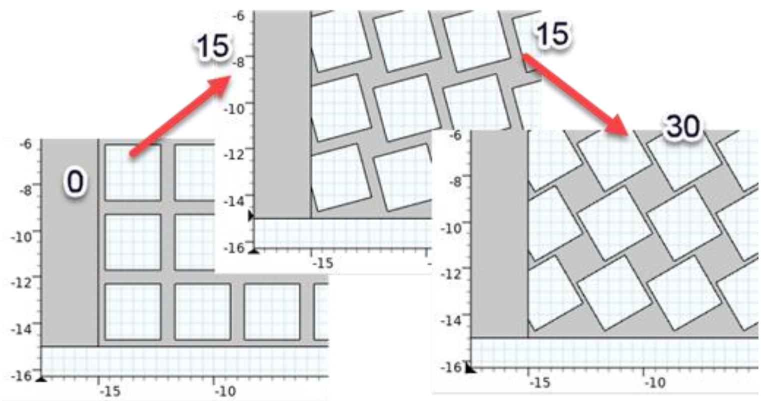



**FIGURE 6.** Examples of grids with rotated cells

Based on the simulation results (a total of 36 possible combinations was obtained, a table of results was obtained (see repository). The table 5 contains the results of calculations in the form of displacements and the values of Young's modulus for all combinations of factors. After calculating the multiple regression equation, it was found that the number of cells is statistically insignificant, therefore finally get the formula 1 and Table 5:

**TABLE 5.** Calculation of Young's modulus of a lattice sample (Young's modulus of solid material 2300 MPa)

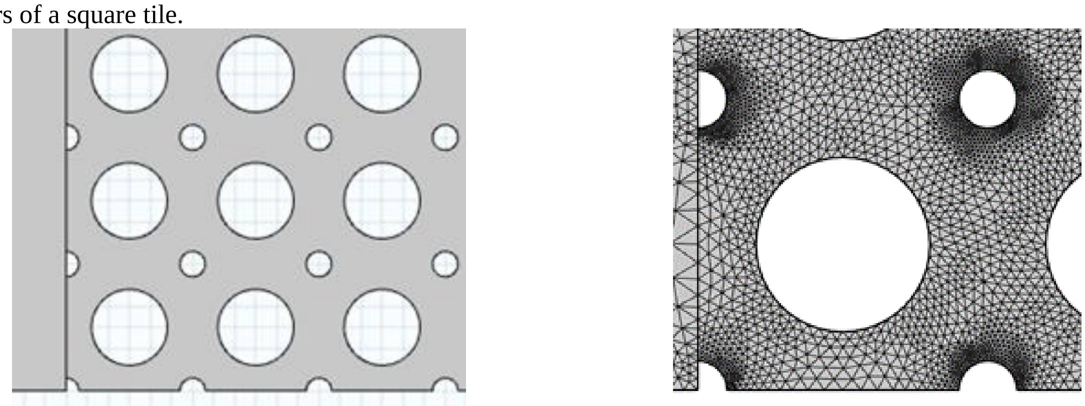
| **N=36** | **R2adj=0.99** | | |
|---|---|---|---|
| | **b** | **Std.Err.of b** | **p-value** |
| Intercept | -141.347 | 16.22240 | 0.000000 |
| kwall | 5647.500 | 99.34151 | 0.000000 |
| ang1 (deg) | -9.075 | 0.49671 | 0.000000 |

$$E_2 = -141.35 + 5647.5 \times kwall - 9.075 \times ang1 \quad (1)$$

Where $E_2$ – calculated Young's modulus of the cellular sample, kwall – relative cell wall thickness, ang1 – cell rotation angle (in degrees)

When the cell is rotated, the walls of the structure work both in compression and in bending, since they receive an additional bending load (from the obvious relations it follows: if the number of cells is K, then the load is proportional to one wall P/2K, and taking into account the rotation of the cell, the longitudinal load will be proportional P/2K cos(ang1) and transverse - P/2K sin(ang1)). This explains the minus sign for the angular component in the model.

Consider in a similar way a sponge-like mesh formed by circles of different diameters located in the center and corners of a square tile.



a) b)

**FIGURE 7.** The structure formed by holes of different diameters (a) and the grid (b)

The mesh area is filled with square cells (see Fig. 7), the diameters of the holes are set relative to the size of the indicated squares (see Fig. 3).

Define the radius of the central hole as 0.2, 0.3, and 0.4 of the cell size, and the corner ones as the wall thickness earlier. The grid may be as shown in Fig. 7.

Then (we present the results without detailed calculations):

**TABLE 6.** Calculation of the Young's modulus of a mesh sample with holes (Young's modulus of solid material 2300 MPa) (Young's modulus of solid material 2300 MPa)

| **N=36** | **R2adj=0.99** | | |
|---|---|---|---|
| | **b** | **Std.Err.of b** | **p-value** |
| Intercept | 2606.79 | 27.5159 | 0.000000 |
| kwall | -3915.83 | 127.374 | 0.000000 |
| khole | -4184.17 | 63.6870 | 0.000000 |

$$E_2 = 2607 - 3916 \times kwall - 4184 \times khole \quad (2)$$

Where $E_2$ – is the calculated Young's modulus of the lattice sample, kwall – is the relative radius of the corner holes, khole – is the relative radius of the central hole of the cell (the actual values of the radius are obtained by the formula $r = k \times a$, where a – is the size of the mesh cell), according to the meaning of the problem khole<0.5.

## THE DISCUSSION OF THE RESULTS

Lattice structures, as noted in the introduction, are not fundamentally new, but their targeted use can be very useful [1].

As a result of finite element modeling, it was possible to obtain relatively simple formulas for calculating the Young modulus of the above grids.

Due to this, it is possible to replace the lattice region with a virtual continuous material, which allows one to increase the calculation to 5-10 time.

Improving the speed of modeling in itself, although useful, is not an end in itself. The ability to control the strength of the material allows in some cases to abandon the use of topological optimization tools and, moreover, generative (generative) design. Instead of forming complex and unnatural geometry with the indicated methods, it is enough to fill the areas with lattice grids of known parameters.

## CONCLUSION

In this paper, we consider relatively simple flat grids. The mosaic theory allows us to say that there are 8 variants of regular lattices, and the number of irregular flat lattices is almost infinite, not to mention volumetric structures.

In this work, only the Young's modulus is considered, moreover, under conditions of pure tension or compression. Even under these conditions, when the cells rotate, nonlinear material reactions occur.

The article does not use other calculation methods than the finite element method, although thin bridges, generally speaking, should be calculated as membranes, taking into account the effect of stability loss and also phenomena at the points of their intersection.

The use of lattice structures can be expanded, since they affect not only strength, but also, for example, thermal conductivity, acoustic conductivity.

Thus, the presented work can be considered as the beginning of a series of studies carried out in the interests of the enterprises of the Pskov Electrotechnical Industrial Cluster and ZETO CJSC (Velikiye Luki) in particular.

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Full versions of the material presented in the article are available in the GitHub repository at:: https://github.com/Alex-Samarkin/Don2

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