Development of a Computational Model of Lattice Structure

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Abstract. This paper deals with the description of the mechanical properties of the plastic lattice structure. These structures are nowadays used in the additive manufacturing. The final goal was to found a mathematical formula, which allowed the FEM simulation of the described lattice structures as the structure were a solid material. The formula stablishes relationship between the original material Young Modulus and weight ratio of the lattice cell. Validation of the formula was performed by the mechanical test. The basis of the study was real testing and measurement, analysis of simulation using the finite element method and the Gibson-Ashby model with some enhancements to get to results within 95% of reliability.

1 Introduction

The concept of cellular structures, including foams, honeycombs, lattices, and similar constructions, comes from retaining material only in the vital regions of a part to attain a lightweight structure, while maintaining mechanical properties such as high strength and energy absorption [1].
Additive manufacturing is a rapidly prototyping and developing technology that is growing faster in all sectors of industry, making it possible to show the first idea of the product to the customer in a short time. In this paper results of simulations and real testing are deeply described and used to get as near as it is possible from the real behaviour of the lattice structures. With that it is possible to reduce simulating time, allowing a better meshing of the parts with lattice structures. The applicability of this work is way further than a research, since the basis of optimization in all areas (naval, automotive, aerospace, medicine, and others) is a light weight structure with the desired strength [2].

1.1 Lattice specimens

The 3 lattice structures were chosen due to its versatility and easily modifiable parameters. All samples were made out of a single pattern cell, repeated block with dimensions of 30x30x30 mm.

- Primitive: Centred circles on each face of the square brick, connected to its centre.
- Octa: Centred circles on each face, connected to the adjacent face with a 90° angle.
- Spherical: The structure made from a brick with a hole made by a centred sphere in it.

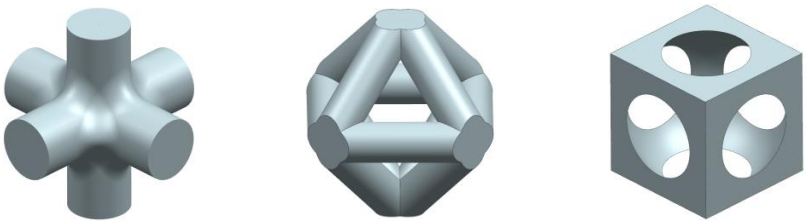

Fig. 1. Used lattice structures (Primitive, octa and spherical – left to right).

1.2 Design of structures

The structures were modelled in CAx software Siemens NX 12 with defined expressions, such as diameter and cell size, to make it easy to change the structure. Afterwards they were simulated in NX Nastran solver with solution SOL 101 (Linear Statics-Global Constraints). Most elements were meshed with element size between 0.3 and 0.8 mm using tetrahedral quadratic elements (CTETRA10). They were fixed at the bottom base and a force of 167 N was applied on the top surface.
The material used the HP 3D High Reusability PA 12. As long as the formula correlates original material Young Modulus (E), weight ratio (Wr) and constraints obtained from the tests, the formula works for different type of materials and young modulus.

1.3 Simulation and determination of behaviour

All the structures followed the same steps in the equation finding process. Several points of different Wr, cell size and diameter were simulated and the area of Hooke's law validity studied. Before the block was simulated, it was divided into one quarter because of its symmetric behaviour, allowing the simulation to have a better mesh refinement and run much faster.

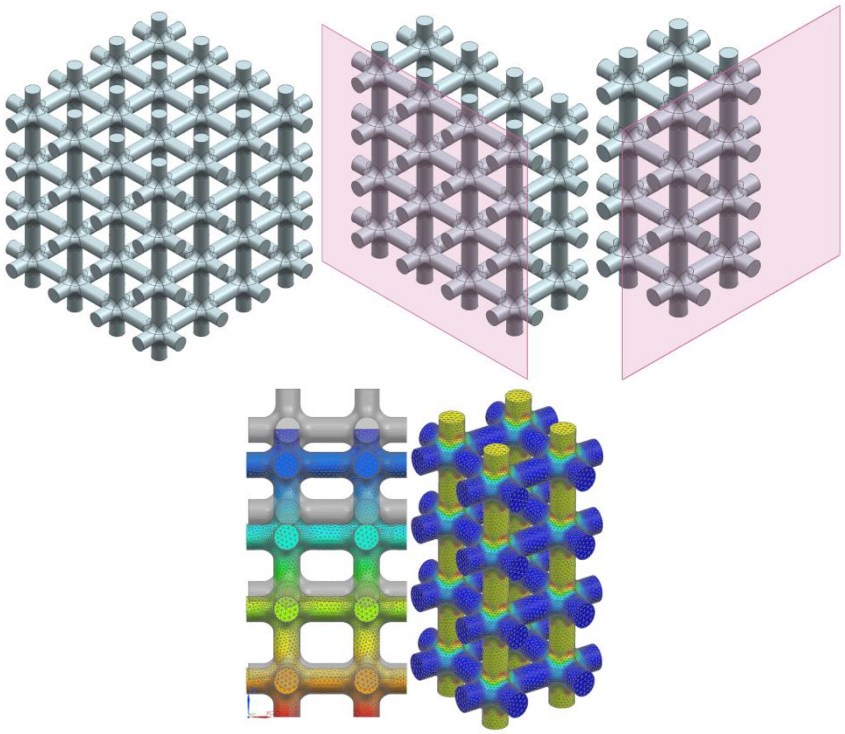

Fig. 2. Block design with results from simulation for primitive lattice cell.

In order to get the most reliable results, it was simulated several points of weight ratio (Wr) and various equation fitting were made to get the best answer considering all the usable Wr for a generic structure. To get to Young Modulus of each structure, it was considered its displacement, area of the full brick and initial length. This way the lattice structure is described as a new material completely filled [3]

$$E = \frac{\sigma(\varepsilon)}{\varepsilon} = \frac{F/A}{\Delta L/Lo} = \frac{F * Lo}{A * \Delta L}$$

The used data from the primitive structure is shown below in the table of Young modulus reached from individual simulations:

Cell Size [mm]	Diameter [mm]	Wr [%]	Young modulus estimatedfrom simulation[MPa]
7.5	1	3.94%	25.54
7.5	2.37	20.20%	163.25
10	3.35	22.49%	186.38
11	3.74	23.10%	192.66
9	3.35	27.21%	236.68
7.5	2.8	27.34%	237.89
10	3.74	27.43%	238.57

It is possible to calculate the Young Modulus of the lattice cell approaching it to a full material brick, according to it's Wr. This way we will be able to simulate a brick of lattice structure as if it was a different full filled material and much faster, depending on the equation with the real material, weight ratio (Wr) variable and constants obtained from the simulation and real testing. [4, 5]. Following graphs shows individual points from simulation and approximation by function.

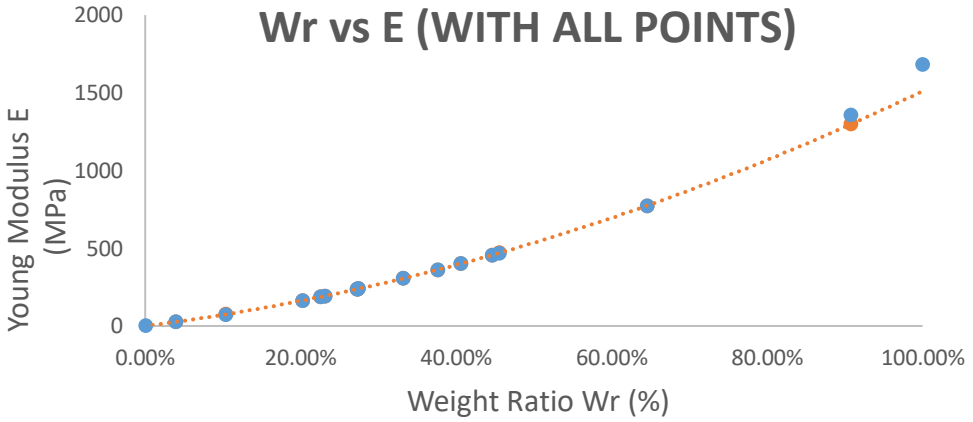

Fig. 3. Approximation of the Young modulus function (polygonal function) with respect to the individual results.

1.4 Young modulus description for the primitive structure

After getting the data of many simulations, and approaching the points to get a bigger range of correct results, it's found the final equation to describe the primitive lattice structure Young Modulus. The polynomial equation works in a range of 3 to 90% of weight ratio with errors between the simulation results of the real structure and the equation approached one lower than 5%.

$E_{primitive} = E * (0.5233 * w_r^2 + 0.375 * w_r)$; from 3 to 90% of weight ratio

1.5 Young modulus description for the octa structure

The first range of values is defined from 6 to 28% of weight ratio. The second range defines the behaviour from 28 to 100% of weight ratio and can be approximated to a simple quadratic equation within 95% of reliability.

$$E_{octa} = E * (0.6319 * w_r^2 + 0.1012 * w_r) \quad \text{; from 6 to 28\% of weight ratio}$$

$$E_{octa} = E * w_r^2 \quad \text{; from 28 to 100\% of weight ratio}$$

1.6 Young modulus description for the spherical structure

After the analysis of the simulation results, it was possible to determinate an equation that described the young Modulus of the spherical lattice structure from 13 to 45.5% of weight ratio with over 96% of reliability.

$$E_{spherical} = E * (0.981 * w_r^2 + 0.2129 * w_r) \quad \text{; from 13 to 45.5\% of weight ratio}$$

1.7 Validation

A simulation of a generic part using the primitive pattern to optimize the structure was used with the real structure, and the structure approach defined by the equation.
The boundary conditions and parameters for the simulation were: the lattice structure have 40.59% of Weight Ratio (Wr). The point number 1 is fixed in x direction and have a force applied in it of 1000 N, on the internal surface of the hole. Point number 2 is fixed in all directions and rotation axis except by the z rotation axis [6].
Comparing two simulations of the example structure below, it's possible to see that this method allowed us to reduce the simulation time from more than 1 hour and 30 minutes to less than 7 minutes (with less computational power) and with over 95% of accuracy.
By creating a new material with the found formula, correlating the applied geometry and the specific weight ratio, the simulation was able to measure the displacement of the boomerang geometry structure. The simulation of the real lattice found 2.229 mm of maximum displacement and the new method found 2.133 mm. The error is only 4.3%.

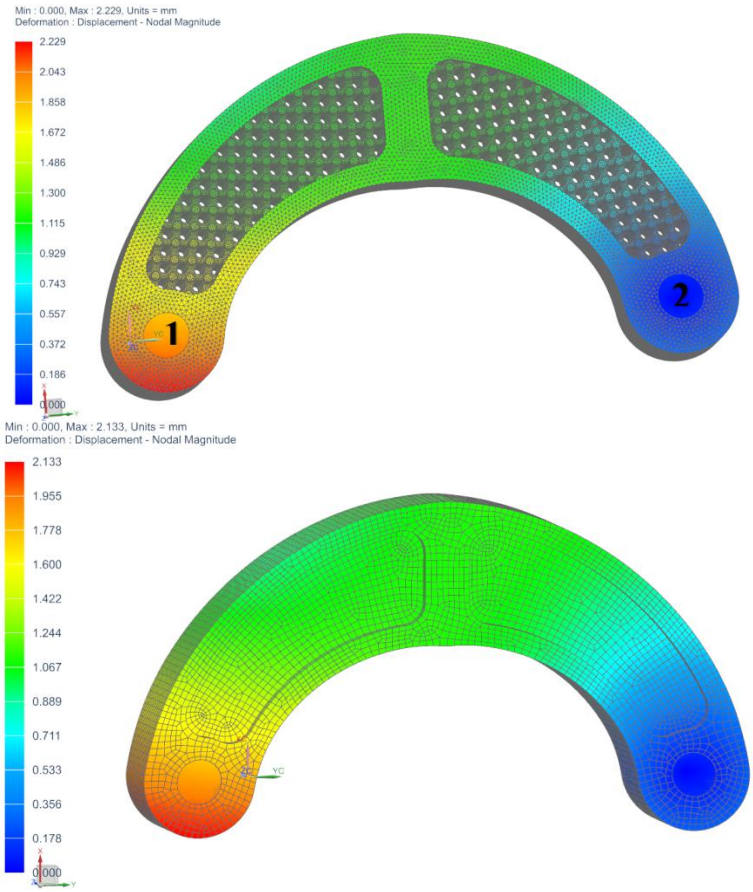

Fig. 4. Comparing of the results of the regular part with lattice structure (above) and simplified geometry (bellow).

1.8 Real tests and results

The real testing was performed in the electromechanical testing device ZWICK/Roell Z250. The standard ISO 604 - 'Determination of compressive properties' was considered during testing.

After the measurement of the real Young Modulus, it's possible to predict the Lattice structure's Young Modulus based on it's weight ratio. For each one of the structures below, it's showed the predicted answer and the results of the compressive test [7,8].

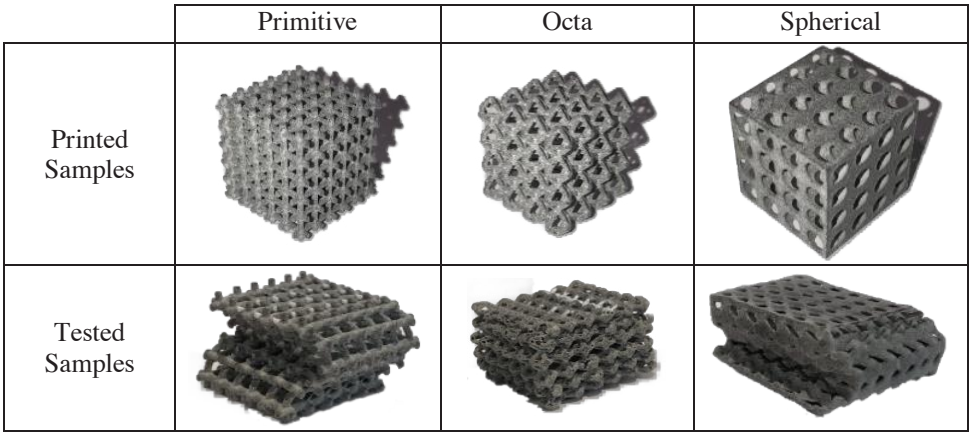

Fig. 5. Example of printed samples before and after testing.

To determinate the Young Modulus of the printed parts, the acquired data from the compression tests were studied and changed. From the test we got the magnitude of the force applied and the displacement of the specimen. These data were changed to plot a stress-strain graphic as the one following [9,10].

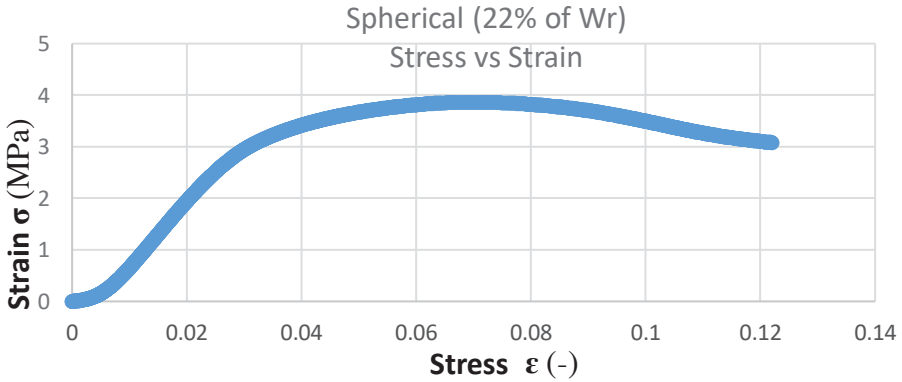

Fig. 6. Example of the stress-strain curve for selected lattice cell.

Therefore, the elastic (linear) part of the graphic was used to determinate the Young Modulus for each printed sample.The simulation results diverged less than 5%, the error to the real printed part is way bigger. For further studies it is recommended to somehow predict the behaviour after the part is printed, to have since the design step what will be the final condition of the parts. The real error between calculated and tested Young modulus was around 20%. It is also caused by the technology of additive manufacturing and non-homogenity of the material.

1.9 Conclusion

This research main goal was to determinate a formula that allowed the simulation to run faster. Many structures of each type were simulated and compared to find the final equation, which had a satisfactory answer. All 3 equations have a good working range and

rigorous accuracy, getting results with less than 5% discrepancy. The formula works for different materials reaching its objective.
The research showed a difference between the virtual simulation and the real test measurement. The difference stayedaround 20% from the solver. It is caused by the usage of additive technology. For further studies, the behaviour of the printing method should be studied and considered getting to a final answer more appropriate and near the results of the virtual testing.

Acknowledgments

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