2D NUMERICAL SIMULATION OF AUXETIC METAMATERIALS BASED ON GLOBAL DIC

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Abstract. This work discusses a novel approach to simulate metallic auxetic structures manufactured via Selective Laser Melting (SLM). SLM-manufactured metamaterials are difficult to simulate accurately based on nominal geometry and bulk material behaviour. The geometry after printing is different from the nominal CAD geometry. Artefacts due to the printing process such as pores yield a material behaviour which depends on the surface/volume ratio. We investigate a phenomenological approach to obtain a simulation model calibrated with experimental data and Digital Image Correlation (DIC). Finite Element based global DIC as suggested by Hild [1,2] allows for obtaining accurate displacement fields, consistent with the true deformation of the lattice structure. Based on the nominal CAD geometry, a simplified parametrized simulation model is created, exploiting the abundant symmetries of lattice structures. Using nodal displacements from DIC in combination with the expected forces from an experiment, the model is calibrated via LS-OPT. The approach is applied to an antitetrachiral, auxetic structure. Furthermore, we discuss the accuracy of the approach, its applicability to other structures and possible extension into 3D space.

1 Introduction

This work discusses a novel approach to simulate metallic auxetic structures manufactured via Selective Laser Melting (SLM). Auxetic metamaterials are structures exhibiting negative Poisson's ratio. When loaded, an auxetic structure reacts with element rotation. These rotations are responsible for the auxetic effect. Metallic structures with auxetic properties show interesting behaviour in comparison to conventional non-auxetic metamaterials, especially when loaded at a high rate of strain, such as increased yield strength, higher energy absorption [3] and possibly enhanced energy dissipation [4]. This makes the materials an interesting candidate for application in the automotive sector, especially in crash applications.

SLM-manufactured metamaterials are difficult to simulate using analytical models: The geometry obtained after printing differs from the nominal CAD geometry (Fig. 1). The printing process causes defects like porosity and the base material behaves differently in bulk

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than within a slender structure. Therefore, purely analytical models do not yield realistic results, especially in case of plasticity. Furthermore, analytical models tend to yield either the correct deformation or the resultant force, but not both. Consequently, a new approach is needed, that connects experiment to simulation and yields realistic results.

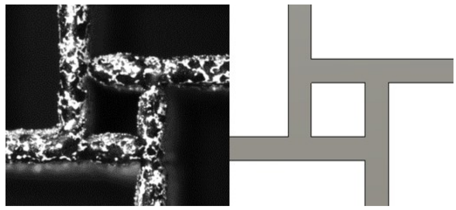

Fig. 1. Difference between a SLM printed antitetrachiral unit cell out of Scalmalloy® and its CAD equivalent. Printed geometry shows change in thickness and geometrical proportions in comparison to its CAD equivalent.

2 Manufacturing and Experimental Setup

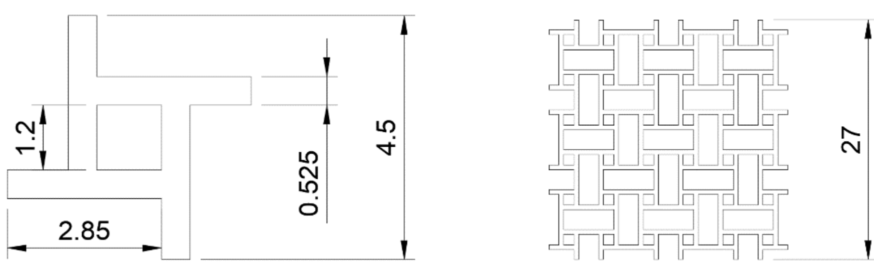

Fig. 2. Unit cell and the resulting antitetrachiral structure by repeatedly mirroring the unit cell in two directions in space. All dimensions in mm.

In order to simulate, experimental data is needed. The data is obtained via quasi-static compression testing. The geometry chosen for this work is an antitetrachiral structure based of the geometry found in [5]. The structure was chosen due to its auxeticity and remarkably low shear modulus. Specimens based on the dimensions depicted in Fig. 2 were printed using Selective Laser Melting SLM. The printing process was performed by Fraunhofer Ernst-Mach-Institute, EMI. The material chosen was Scalmalloy®. Scalmalloy® is a Scandium modified Aluminium-Magnesium alloy that features a specific tensile strength and elongation at break comparable to some titanium alloys. The material was developed for lightweight crash-absorbing structures as used in automotive and aerospace engineering [6].

The structure is compressed at 4.32 mm/min using a Zwick Universal testing machine. To apply DIC in addition to the force measurement, specimens are recorded as grayscale images with a resolution of 4096 x 3000 px at 1 fps using a Basler ace 2 Camera. These recordings are used to analyse the deformation in detail.

3 Digital Image Correlation

To provide an in-depth understanding of a structure and collect data in order to accurately model and simulate the metamaterial, a detailed analysis of the structural response is mandatory. The analysis is performed using Digital Image Correlation (DIC). DIC registers two or more images of the same scene and extracts a displacement field.

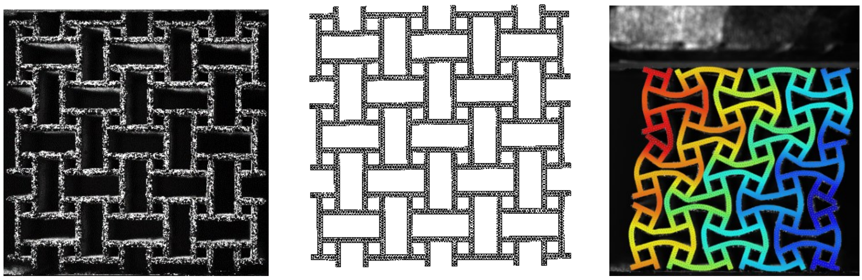

Fig. 3. On the left is the recorded structure prior to deformation. In the middle is the FE mesh based on the CAD model of the structure. The mesh is applied to the surface of the structure in its initial state. On the right, the structure including the mesh have already been deformed.

Global Finite Element based DIC combines DIC with a finite element mesh. Since the pictures used in DIC already have to be divided in sub-images, it is natural to consider a structure directly comparable to FE simulations. This method results in a displacement field, which deforms depending on the deformation of the structure, as shown in Fig. 3 [1,2,7].

The displacement field in this work was calculated using the software Correli provided by François Hild, CNRS senior researcher at the Laboratory of Mechanics and Technology, ENS Paris-Saclay.

4 Finite Element Simulation

4.1 Model Setup

In comparison to typical model calibration techniques, this work does not aim to calculate a material model. The material model is calculated using a separate set of quasi-static tests utilizing tensile specimens printed out of the same material.

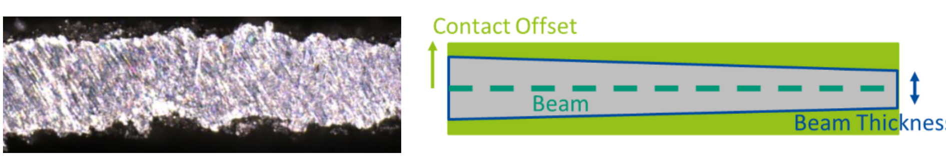

Fig. 4. Cross section of a SLM printed structural component printed out of Scalmalloy and its model equivalent, depicting its solid core encased by an uneven layer of material.

The model in this work focuses on the influence of geometrical parameters on structural behaviour. Looking at the cross section of a SLM printed metallic structural component a depicted in Fig. 4, it consists of a solid core surrounded by an uneven surface layer of material. This allows for dividing the beam into two components: A solid core which mainly influences the stiffness of the beam, and the surrounding layer which encases the core without influencing its base characteristics.

The simplest approach to define this behaviour in a model is using beam elements combined with a contact constraint. Each node gets an assigned beam thickness. The beam thickness is interpolated between to nodes to ensure a smooth transition. This setup defines the stiffness and deformation of the beam in case of a load. Since the structure experiences a large global deformation, deformation in case of contact cannot be described by beam thicknesses alone. A surface layer equivalent has to be introduced, which is done by using contact offset. Since this component only becomes relevant in case of contact, it does not influence the physical behaviour of the beam, but it influences the point of densification.

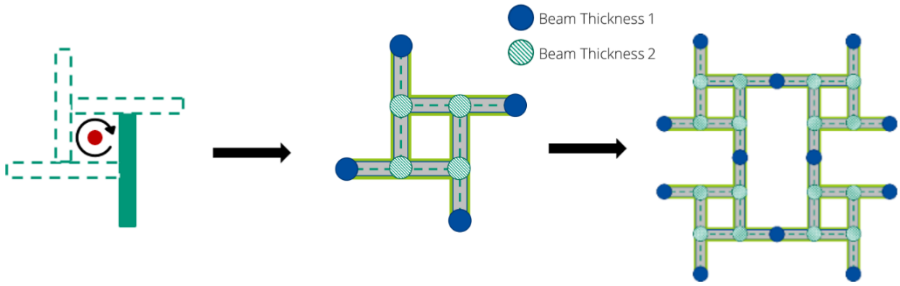

Fig. 5. Antitetrachiral structure, starting with the rotational symmetry of the smallest component, resulting in the unit cell with sets of nodes with the same properties, reducing the number of total parameters for the whole structure. Unit cell is mirrored in two directions in space creating the antitetrachiral structure. The number of parameters stays the same.

We exploit the two-axial symmetry of the lattice structure and the rotational symmetry in the unit cell itself to reduce the model complexity to only two beam thickness parameters and one contact offset parameter (see Fig. 5).

Several experiments and simulations of the antitetrachiral structure have shown the structure to be very sensitive to a change in boundary conditions. Therefore, to be as close to the experiment as possible, boundary conditions are applied based on the displacement obtained via DIC. Boundary nodes are identified, which are located at the very top and bottom of the structure. The rest of the nodes can move freely. Each boundary node gets assigned two prescribed motions, in x and y direction.

4.2 Model Calibration

The model is calibrated using LS-OPT. LS-OPT is a design optimization software tightly interfacing with simulation software LS-DYNA. In this work it is utilized to calculate geometrical model parameters by minimizing the Normalized Root Mean Squared Error NRMSE [8, 9] between the experimental data and the simulation result.

The optimization chosen is a sequential strategy with domain reduction. The process utilized by LS-OPT is widely known as Response Surface Methodology RSM. It starts with a setup, where the parameters and their respective region of interest are defined. After the setup, LS-OPT runs a number of simulations with different sets of parameters. The parameters are chosen within the domain defined prior based on D-optimal design. Using the computed simulation results, NRMSE is calculated.

The error consists of two parts: the force and the displacement error. The force error is calculated by dividing the root of the Mean Square Error MSE by the difference between the maximum and minimum target value aka experimental value.

$$NRMSE_F = \sqrt{MSE_F} \,/\, (T_{F_{max}} - T_{F_{min}}) \tag{1}$$

In case of nodal displacement, NRMSE is first calculated for each individual directional MSE. The sum of all nodal errors is taken and divided by the total number of nodes m. This reduces the number of displacement errors to one value, which represents the average error over all nodes.

$$NRMSE_D = \frac{1}{2m} \sum_{j=1}^{m} \left[\frac{\sqrt{MSE_{XD}}}{(T_{XD_{max}} - T_{XD_{min}})} + \frac{\sqrt{MSE_{YD}}}{(T_{YD_{max}} - T_{YD_{min}})} \right]_j \tag{2}$$

Force and displacement error are combined, resulting in the total error of the system.

$$NRMSE = \frac{1}{2}\,[NRMSE_F + NRMSE_D] \qquad (3)$$

The calculation is performed by an external script. The script loads the results, calculates the error and returns the error value to LS-OPT in form of a response. The response values are utilized by LS-OPT to build a quadratic polynomial metamodel, creating a response surface. By locating the minimum of the response surface, a subregion within the region of interest is created. This subregion is used to calculate new sets of parameters and run new simulations. With each iteration the subregion is reduced further until either the design change becomes too small or a defined number of iterations is reached.

5 Results

The calibration was terminated after 40 iterations, yielding following results:

Table 1. Parameter and Error Results.

Beam Thickness 1	0.56 mm	Displacement Error	0.054
Beam Thickness 2	0.29 mm	Force Error	0.073
Contact Offset	0.32 mm (0.64 mm total)	Total Error	0.063

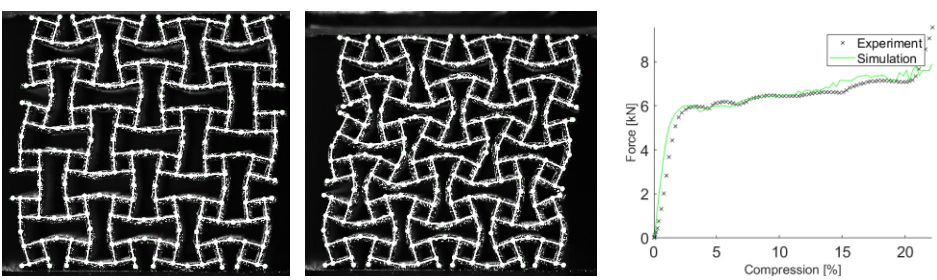

Fig. 6. Images of the experiment (gray speckle pattern) overlayed with the simulation results (white) at 10 % and 20 % compression. The difference between experimental and simulation deformation is hardly visible.

As depicted in Fig. 6 the simulation manages to accurately reproduce the same structural deformation over time as the experiment. Additionally, forces of the simulation are comparable to experimental data.

Comparing the resulting parameters to each other, both beam thicknesses are smaller than the total contact offset of the beam. This confirms the assumption made in 4.1, since the solid core always has to be smaller in thickness than the total size of the structural component. Furthermore, the total contact offset is comparable to the average thickness of the printed structure, which was measured to be on average 0.64 mm. This shows that the parameters calculated in this way are not arbitrary number, but have physical significance.

6 Conclusion

In this work a novel phenomenological approach to simulation of 2D structures is introduced. A SLM printed structure is assumed to be build up out of a solid core encased in a layer of additional material. The structure is discretized using beam elements with varying beam thicknesses combined with a contact offset. The parameters are calculated from experimental data using force and the full displacement field obtained from Finite Element based DIC. The calibrated simulation shows good agreement with the structural deformation and experimentally measured force data. A comparison between the parameters confirms the assumption made about the composition of the printed structure. Additionally, the comparison between the total contact offset and the real thickness of the structure demonstrates that the calculated quantity is not an arbitrary number.

Quality of results is dependent on the experimental setup and the quality of the displacement field. Especially the displacement field can be prone to noise, which may change the results. Furthermore, the setup of boundary conditions has a high impact on the simulation results and has to be as close to the experimental setup is possible.

However, it is amazing how the model manages to replicate the complex behaviour of the structure as observed in the experiment, even though the model is a significant simplification and can be described by only a total of three parameters. A calibrated model can be used to investigate the behaviour of the structure under different conditions. Furthermore, this approach can be applied to every 2D structure which can be discretised using beam elements. In the future this procedure is planned for application on 3D structures utilizing ex- and in-situ CT experiments in combination with Digital Volume Correlation DVC.

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