INL/CON-23-75629-Revision-0

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Changing the World's Energy Future

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March 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

COMPUTER-AIDED LATTICE DESIGN AND ADVANCED MODELING FOR THE DEVELOPMENT OF LIGHTWEIGHT STRUCTURAL MATERIALS

Rongjie Song[1], Michael Moorehead[2], Dewen Yushu[3], Jia-Hong Ke[4]

[1] Distinguished Staff Scientist, (rongjie.song@inl.gov); [2] Nuclear Materials Scientist; [3,4] Computational Scientist

ABSTRACT

The notion of a “fission battery” conveys a vision focused on realizing very simple “plug-and-play” nuclear systems that can be integrated into a variety of applications requiring affordable, reliable energy in the form of electricity and/or heat and function without operations and maintenance staff. Fission batteries require lightweight structural materials to increase their mobility, and the lightweight materials must demonstrate structural resilience under various conditions. The objective of this work is to develop lattice structured lightweight structural material featuring a good combination of mechanical properties using advanced modeling and simulation together with an advanced additive manufacturing technique such as laser powder bed fusion. The preliminary results show that different lattice structures and types can be successfully meshed using nTopology software, and the lattice structure data can be successfully transformed to Multiphysics Object-Oriented Simulation (MOOSE) Environment input. Finite Element Analysis (FEA) displays that, at macro/engineering scale simulation, the weight saving design has an obvious effect on tensile behavior such as effective elastic modulus and yield stress. The novel approaches of this work are (1) development of lattice structures for improved mechanical properties using advanced simulation and modeling techniques; and (2) model predictions of the mechanical properties (e.g., strength and stress distribution) of macroscopic materials in order to preliminarily select a lattice structure for additive manufacturing.

1. INTRODUCTION

Fission batteries are nuclear reactors for customers with heat demands less than 250 MWt—replacing oil and natural gas in a low-carbon economy. Individual fission batteries would have outputs between 5 and 30 MWt. The small fission battery size has two major benefits: (1) the possibility of mass production and (2) ease of transport and leasing with return of used fission batteries to factory for refurbishing and reuse. Comparatively, these two features are lacking in larger conventional reactors, Forsberg and Foss (2023). Fission batteries require lightweight materials for structural applications to realize the envisioned mobility and siting of fission batteries. These materials must also demonstrate structural resilience under various operational, transportation, and external conditions (including rare events such as seismic vibrations, flooding, tsunamis, and fire). This means the materials must feature a good combination of mechanical properties.

Lightweight materials can be achieved using low density elements in the alloying composition, composite, and/or adopting strategic structure design to decrease mass. Additive manufacturing of lattice structured material has proven an attractive method of producing lightweight components. Compared to conventional fabrication methods, lightweighting using additive manufacturing can dramatically improve energy efficiency, performance, and ergonomics while reducing manufacturing costs and emissions, Hailu et al. (2021). However, a wide variety of factors significantly influence the mechanical behavior and structural performance of components made of additively manufactured metals especially when lattice design is involved. In addition to the fabrication process parameters, such factors include surface roughness, residual stresses, heat treatment, and multiaxial stress states. At the microstructural level, defects such as pores and lack of fusion particles, in addition to other microstructural features, all affect mechanical behavior, Charkaluk and Chastand (2018). Therefore, understanding mechanical behavior in lattice structured additive manufactured parts is essential for widely adopting the technique throughout the nuclear industry.

This study focused on lattice parameter design, optimization, and model predictions of the mechanical properties (e.g., strength and stress distribution) of macroscopic materials in order to preliminarily select a lattice structure for additive manufacturing. The variations in relative density (30-90%), unit cell size, cell wall thickness, and blend radius were investigated. The results were to provide a design basis for selecting the appropriate lattice parameters for designing and optimizing the topology of load-bearing structures.

2. LATTICE DESIGN

Additive manufacturing (AM) is defined by the ASTM society as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" ISO/ASTM 52900 (2021). Additive manufacturing software is a type of computer-aided design (CAD) software used in the field of 3D printing. It is typically used to generate virtual 3D models and designs that can be printed on 3D printers. The software enables users to take a digital model and fabricate a physical product from it.

Although Creo is capable of generating latticed structures and the file formats required for printing (e.g., .stl's), the base version of the software is not capable of producing volumetric meshes over the latticed region, which is a necessity for finite element modelling (FEM). It was then found that the vast majority of CAD software is not well suited to produce volumetric meshes of sufficient refinement to perform FEM on lattice structures. Due in part to how the lattice region is explicitly defined and handled in many of the CAD programs that were tested, including Creo, SolidWorks, AutoCAD, Inventor, and Fusion360, attempted operations to mesh over the latticed region of the tensile bars resulted in memory overflows, program crashes, and computer crashes. To address this issue, a new software -nTopology- was trialled which is specifically designed to model complex structures by representing them *implicitly* rather than explicitly. This drastically reduces the computer resources needed to manipulate complex structures.

Using nTopology, the initial simplified models from Creo can be imported and converted into implicit bodies, which can be easily converted into latticed regions and meshed. Additionally, when joining the latticed core region to the shell and connected grips, a blending radius can be applied to smooth the transition between the two regions to minimize stress concentrators. As such, blending radius was added to the list of lattice design parameters to be optimized. Using nTopology, lattice structure and systematically varied lattice design parameters were created. Figure 1 shows that nTopology can successfully mesh the lattice type.

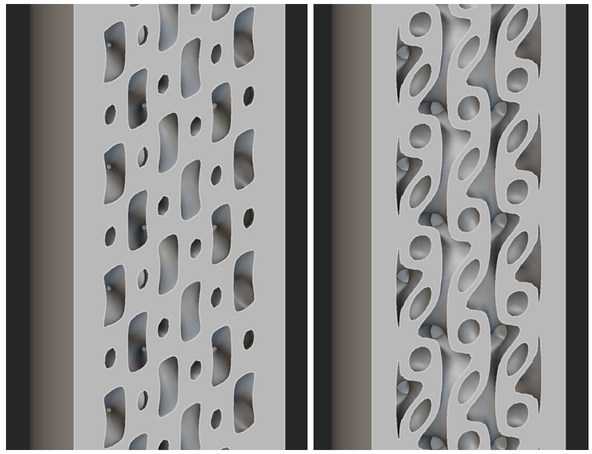


Figure 1. Examples of different lattice types

3. INTERFACE WITH MOOSE

A generalized pipeline and workflow have been developed to construct the interface from Creo, nTopology, to geometries and meshes that can be imported into MOOSE for FEM. The approach takes advantage of the functionalities in MOOSE, FileMeshGenerator and ParsedGenerateSideset, to add and define element sides for setting up boundary conditions. In the simulations of tensile testing, the upper and bottom boundaries were selected by the input parameter "combinatorial_geometry" to define the stress-controlled boundary condition. Tests have been performed to confirm that both the *.unv (I-deas Universal format) and *.inp (Abaqus format) extensions produced by nTopology can be imported into MOOSE to generate the file under Sandia's Exodus II format. A MOOSE input file has been generated for format conversion and the overall pipeline for finite element analysis is summarized in Figure 2. A 3D lattice structure within a tensile bar is first built by Creo, followed by nTopology to optimize the geometry and mesh. The mesh can then be imported to MOOSE to define boundary conditions and finite element modeling.

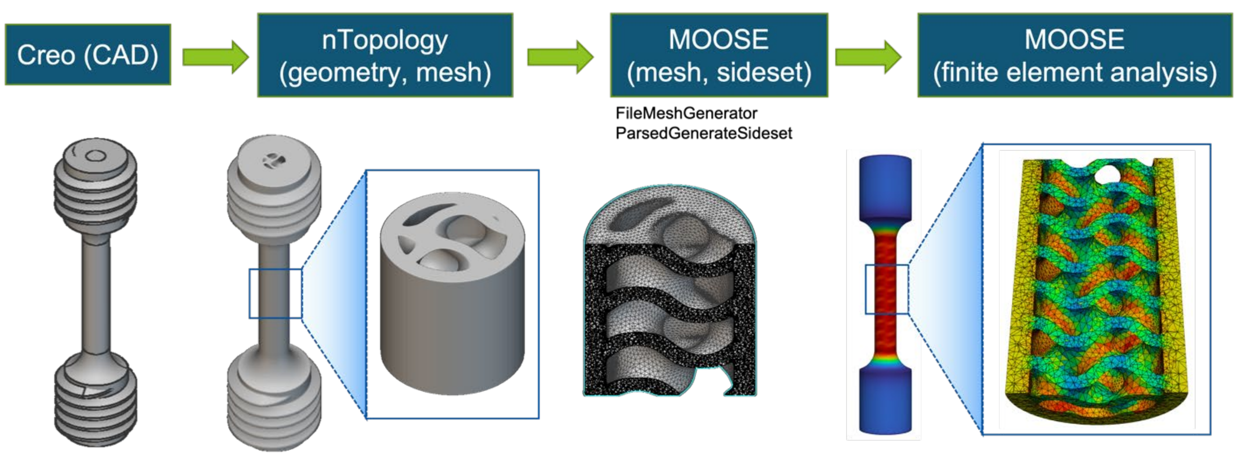


Figure 2. The developed pipeline allowing the construction of geometries and meshes that can be imported to MOOSE for finite element analysis.

4. FINITE ELEMENT MODELING

Idaho National Laboratory's (INL) in-house simulation software MOOSE was employed to simulate the mechanical behavior of the tensile specimen with gyroid structure. The tensile behavior of a representative middle part instead of the entire specimen was simulated, which reduces the computational burden by approximately 90%. An isotropic power law hardening material model is utilized with SS316 bulk material property applied at every material point. To understand the effect of gyroid structure parameters on the mechanical behavior, a batch of simulations were run on gyroid structures with different unit cell size, blending radii (BR), and densities (or weight savings). The stress distributions of the specimens with different unit cell sizes are shown in Figure 3. The stress fields demonstrate clear patterns for each case created by their individual periodic internal structures. The overall magnitude of the stress does not seem to vary much among different unit cell sizes.

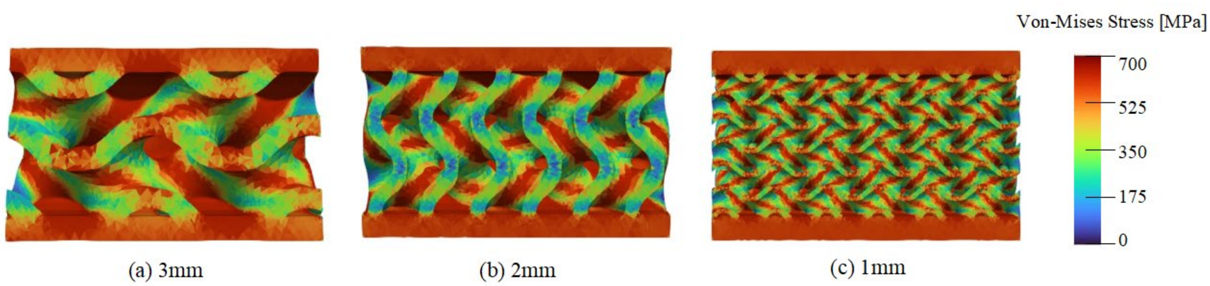


Figure 3. Von-Mises stress fields of specimens with different unit cell sizes. All three structures are 40% dense.

4.1 Macro-mechanical response

To study the macro-mechanical response of the structures, the simulated stress-train curves of the structures were compared. Figure 4 shows the simulated axial stress-strain curve of different structures. The responses of gyroids are compared with that of the solid and shell structures, respectively. Among all three quantities of interest, the density has the most significant effect on the overall macro-mechanical response of the structure. Specifically, a higher density indicates a stronger structure (higher elastic modulus) and a higher yield point (see Figure 4a). Blending radius also plays a role in the mechanical response of the structure, i.e., a larger blending radius makes the structure stronger (see Figure 4b). However, the effect of blending radius is less dominant than the density. Last but not the least, the unit cell size does not play a significant role in the stress-train response (see Figure 4).

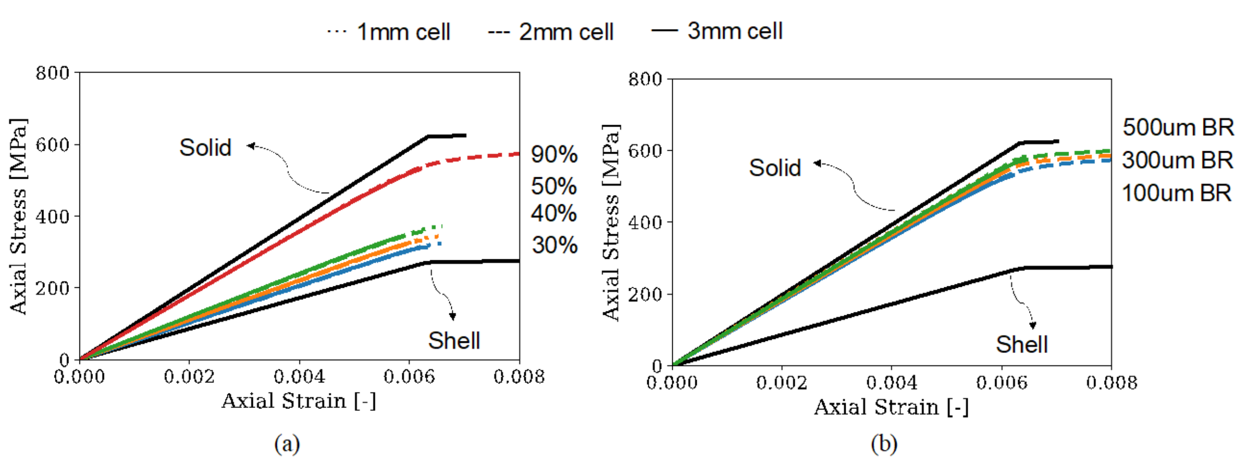
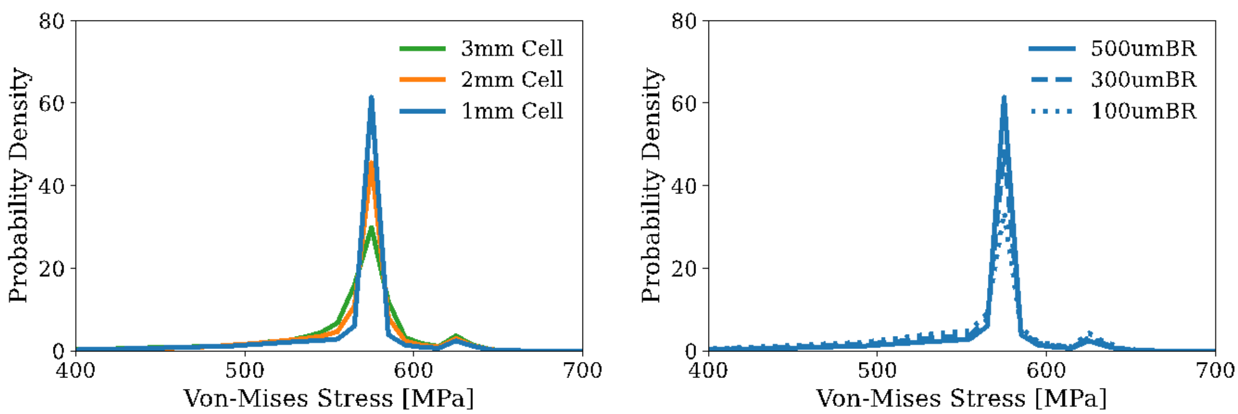


Figure 4. Stress-strain response of different gyroid structures compared with solid material and shell only. (a) Different densities, unit cell sizes with 100 um blending radius. (b) Different blending radii, unit cell sizes with 90% density (10% weight saving).

To study the macro-scale response affected by solid thickness, lattice diameter, density, and unit cell size, a case-by-case comparisons of stress-strain responses of different gyroid structures are included. The solid thickness is shown to has a considerable effect on the mechanical property of the gyroid structure. Specifically, a thicker solid layer result in a stiffer gyroid structure with higher yield point. Meanwhile, the stiffness of the structure decreases with an increased lattice diameter. An increased density makes the gyroid structure stiffer. Nevertheless, the unit cell size does not play an obvious role in the stiffness of the structure.

4.2 Micro-mechanical response

To investigate the micro-mechanical response of the different structures, we choose to compare the probability density function (pdf) of the Von-Mises stress. A concentrated distribution (exhibited by a higher peak) implies a more uniform stress distribution, which indicates a lower possibility of localized stress concentration. Figure 5a shows the pdf for different unit cell sizes (1 mm – 3 mm). The 1 mm unit cell shows the highest peak, indicating the most uniformly distributed stress field. The peak is higher with the decrease of unit cell size, which indicates the more evenly distributed stress field. Therefore, it can be concluded that the unit cell size plays a role in the micro-mechanical response. Specifically, the smaller the unit cell size, the less stress concentration would be expected. Similarly, Figure 5b shows the pdf for different lending radii (100 um – 500 um). With increased blending radius, the height of the peak also increases, meaning a more uniform stress distribution. Therefore, it can be concluded that a larger blending radius would be beneficial in reducing stress concentration.



(a) (b)

Figure 5. Probability density function of the Von-Mises stress. (a) Different unit cell sizes with 500 um blending radius. (b) Different blending radii with 1mm unit cell size. All cases are 90% dense.

5. CONCLUSION

This study investigated appropriate lattice parameters for lattice topology optimization of load-bearing structures. Tensile test specimens with different lattices were created. Each specimen was designed with different relative densities and unit cell parameters. Finite element modelling was carried out to predict the tensile stress of the lattice structure created. It was found that:

- It is important to use the appropriate software for lattice design. nTopology can successfully mesh the unit cell, cell wall, shell, and lattice type.

- A process was successfully developed for transforming lattice structure data into MOOSE input.

- Macro-scale finite element modelling is helpful to simulate the mechanical response under uniaxial tension. The preliminary results showed that weight saving has obvious effect on stress, then bending radius, and minimal effect from unit cell size.

- Micro-mechanical response displayed that smaller unit size and larger bending radius are beneficial for homogeneous stress distribution.

6. REFERENCES

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ACKNOWLEDGEMENT

This work was funded by Idaho National Laboratory's Laboratory Directed Research and Development Program (LDRD project #23A1070-132FP) under DOE Idaho Operations Office Contract DE-AC07-05ID14517.