CHART MagAM

Additive Manufacturing for Structural Components in Superconducting Coils

This report gives an overview of the progress of the CHART MagAM project. The following list contains the work packages (1-3) that were defined in the CHART MagAM project proposal, complemented by additional work packages (4, 5) that were defined during the project together with our project partners at PSI. The leading research assistant changed in mid-2023. In cooperation with PSI, the new work packages (6, 7) were defined and investigated:

1. Experimental investigation on the strength of adhesive joints between structured adherends and epoxy resin.
   Status: Completed (see yearly Report 2022)
2. Digital design workflow for structured adherends for the powered subscale experiment (MagDev project)
   Status: Completed (see yearly Report 2022)
3. Finite element analysis of adhesive joints to predict and optimize the bond strength.
   Status: Aborted (see yearly Report 2022)
4. Infiltration experiments to quantify the advantage of porous structure for the infiltration process with epoxy resin.
   Status: Completed (see yearly Report 2022)
5. Shape adaptive endspacer geometries that contain compliant structures that allows an assembly of a CT-magnet avoiding gaps between endspacers and winding.
   Status: Completed (see yearly Report 2023)
6. Analysis of the potential of structurally graded material in the stress reduction in Dipole Magnets (see Chapter 1)
7. Explorative Study of different material gradings through simulation and mechanical testing (see Chapter 2)

Some of the work packages described in the CHART MagAM project proposal became obsolete after completing the experimental investigation on adhesive joints. Indeed, the results did not show an advantage of structured adherends on adhesive strength at cryogenic test conditions in comparison with AM plain surfaces. Therefore, the FEA investigation for further optimization was aborted after a first investigation (Workpackage 3). Furthermore, the digital design workflow for the structured adherends was adjusted. A digital design workflow only for the *irregular design* was developed and was be applied to design a BOX sample with this type of adhesive interface. The box sample was successfully manufactured, a testing of the sample is still pending. Afterward, four additional work packages were developed to further investigate the use of metal additive manufacturing for the application in superconductive magnets.
This report contains the work packages 6 and 7. For information on previous work packages, refer to the yearly report 2022.

1. Structurally Graded Materials

In the design of racetrack coils, high axial Lorentz Forces occur in the End Sections. Traditionally, the mitigation of thoses stresses is done through carefully tuning of the pretension on the coil heads. In the MagDev 2 project, an additional approach involving the use of multiple end spacers to separate the coils is being explored [1].

Introducing variability in the modulus of elasticity of the end sections presents a new dimension in the design of magnet support structures. This strategy offers the potential to redistribute stress peaks within the coils, achieving a more uniform distribution of Lorentz Forces. Additionally, it enables a more effective preloading of the structures via pretension rods. A preliminary study has demonstrated promising results in reducing simulated stresses on critical epoxy bonds between the support structure and the coils. By selecting an optimal material grading, based on the elastic strain distribution within the support structure, the stress exerted on the coils can be modified. This approach ensures that the coils experience only compressive stresses, effectively eliminating tensile stress (See Figure 1).

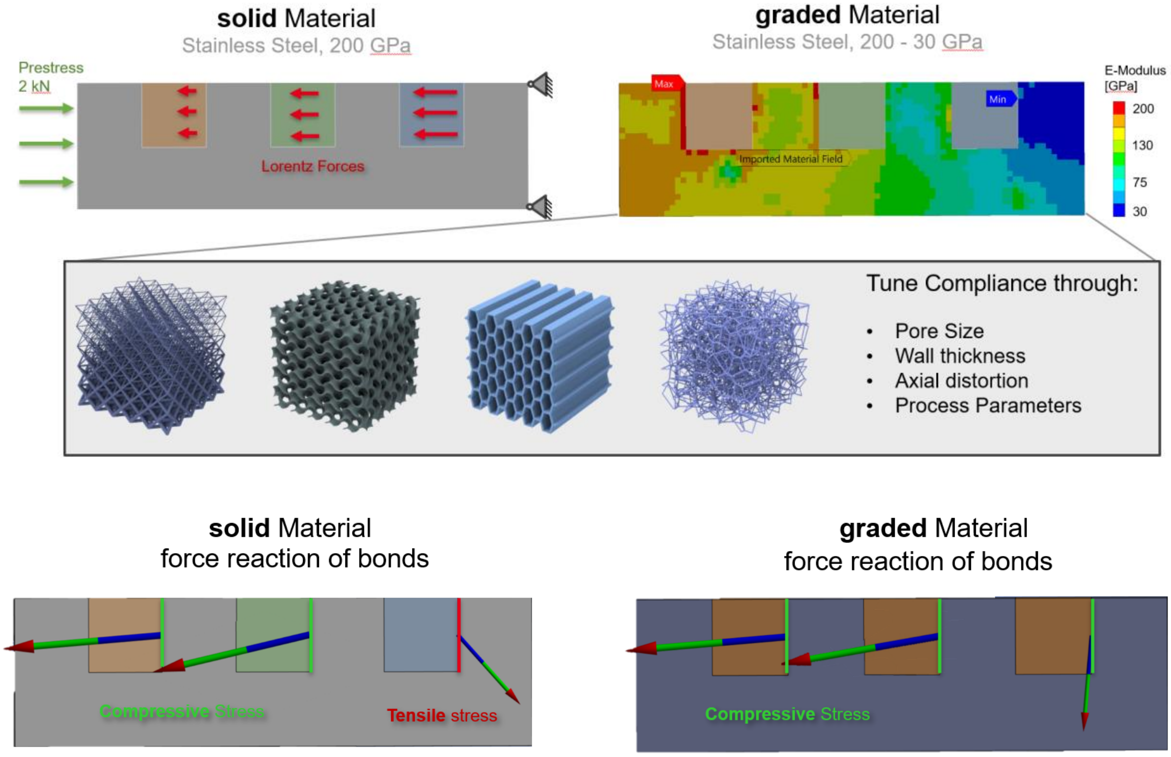

Figure 1 comparison of the force reactions (colored arrows) of the bonds between coil and support structure

Such material grading can be achieved through selectively changing the material density of the Stainless Steel parts and by introducing functional geometries such as lattices or minimal surfaces. The stiffness of those structures can be freely varied by changing the wall thickness of the structure. To facilitate this, a workflow has been developed that correlates the required stiffness at specific points with the wall thickness of the support structure (See Figure 2 and Figure 3).

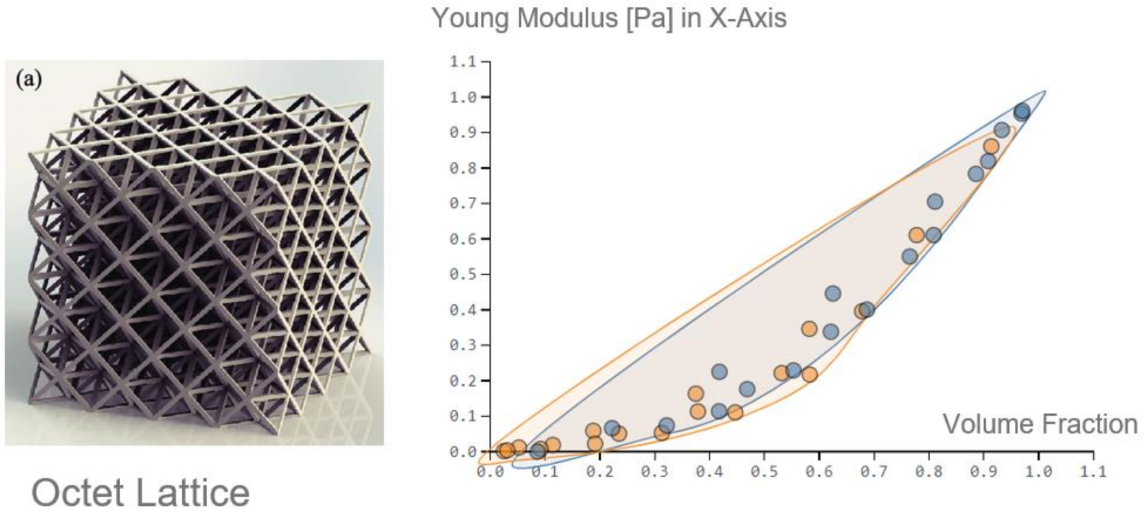

Figure 2 Visualization of the relation between the wall-thickness [Volume Fraction] and elasticity [Youngs Modulus] of an Octet Lattice source: https://latticerobot.com/lattice/BZs0qKuWtOCbWnmLmN97

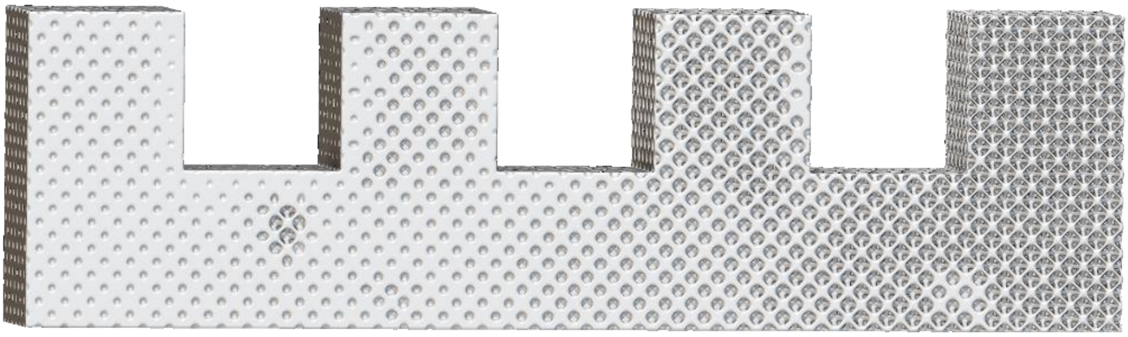

Figure 3 Visualisation of the support structure as graded octet lattice

2. Explorative Study of different material gradings

The exploration of structurally graded materials has revealed promising characteristics. However, this approach necessitates specialized workflows for structure generation, and the resulting geometries pose significant challenges for simulation due to their complex geometry. In this work package, various geometries, including Gyroid, Spherene, and Lattices, will be examined to characterize their grading properties. For this a simplified geometry of a Short Model Coil Head (hereby called “Horseshoe”) was chosen (See Figure 4).

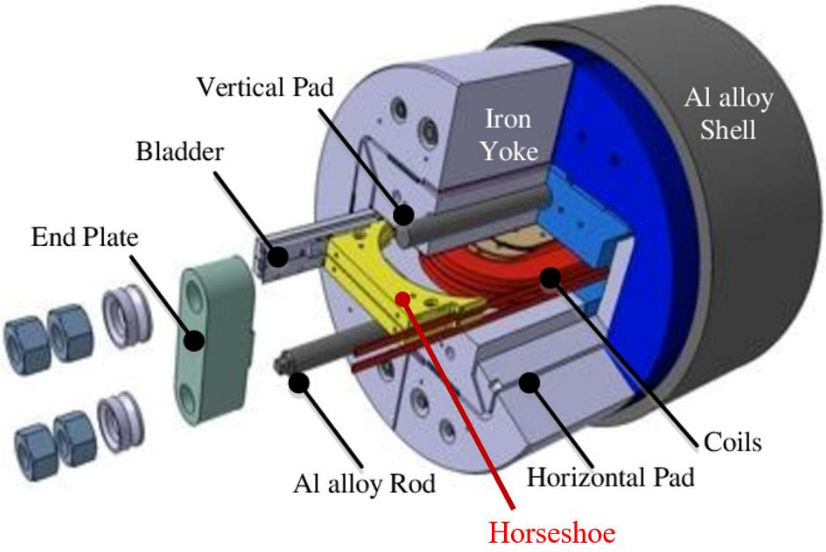

Figure 4 Short Model Coil (SMC) with the Coil Head support structure called horseshoe

First assessing the resulting forces exerted on the coils and the support structure was done by simulating the coil at 15 kA with Ansys Maxwell. The resulting force was used in Ansys Mechanical to analyze the resulting mechanical stresses by using different boundary conditions (see Figure 5).

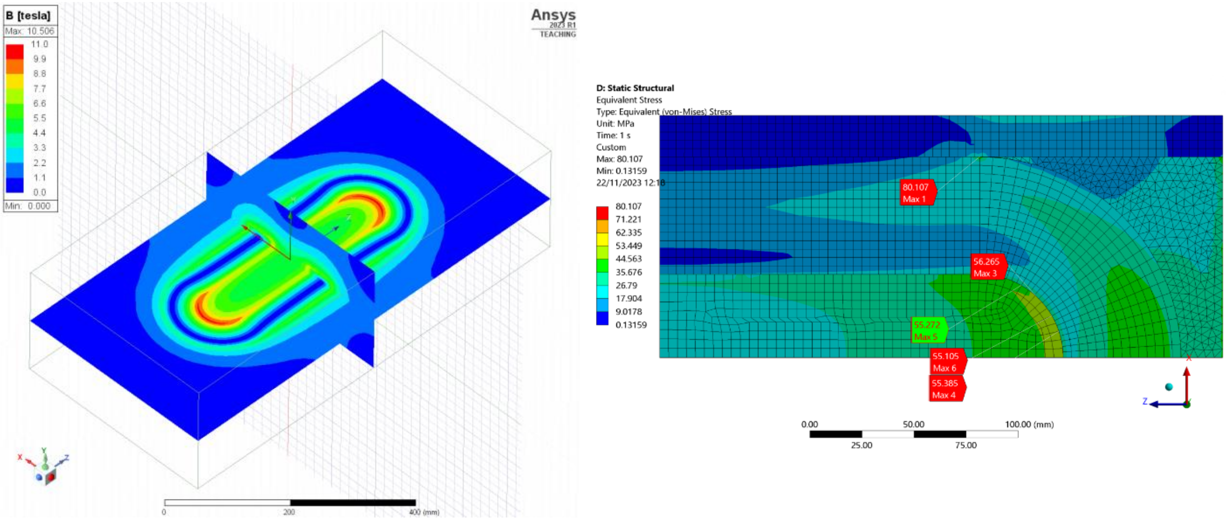

Figure 5 left Image: Maxwell simulation of a loading of the SMC Nb3Sn coils at 15kA. Right image: Equivalent Stresses of the Support Structure without pretension

The next phase involves developing additional workflows to create structures that not only conform to the Horseshoe geometry but also offer the flexibility of grading various properties like wall thickness, pore size or axial distortion (see Figure 6).

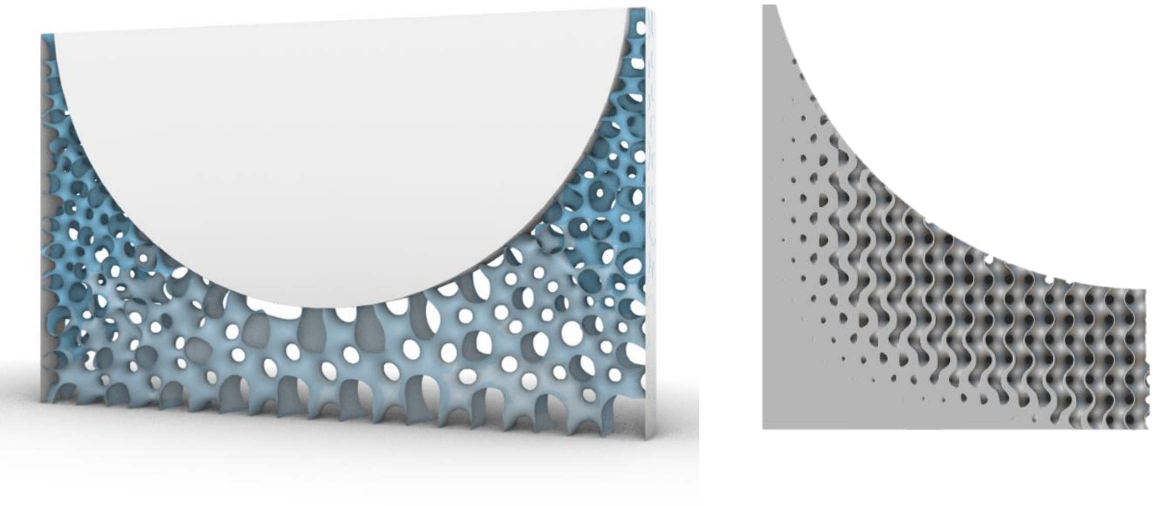

Figure 6 Graded structures: on the left, a spherene with varying the pore size and on the right a gyroid with variable wall thickness

Currently, in an ongoing student thesis, the mechanical properties of these structures are being simulated using thin-shell approximations. The findings from these simulations will eventually be validated through experimental tests (refer to Figure 7).

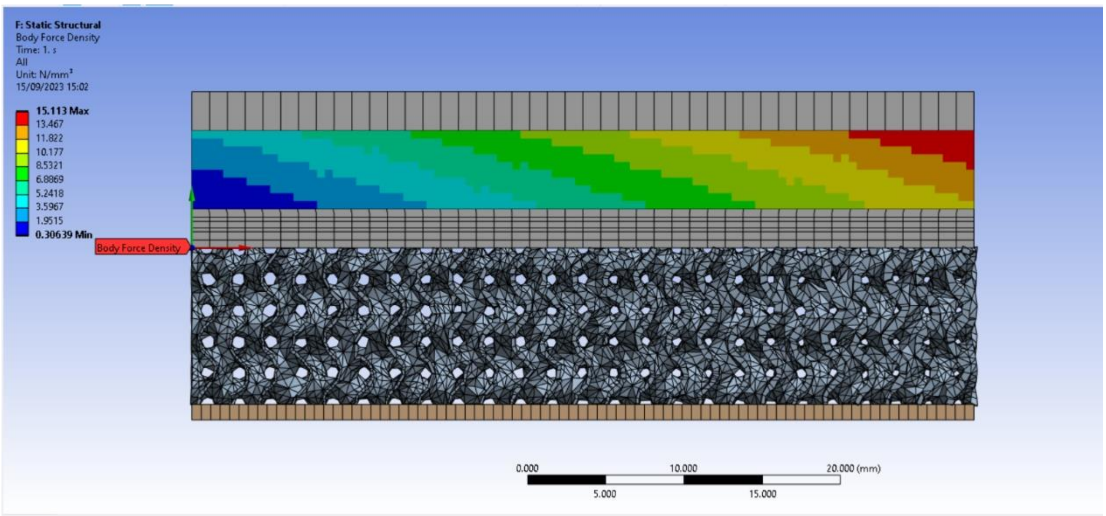

Figure 7 Asymmetric loading of a gyroid with graded wall thickness

3. Team

A comprehensive list of team members in the past year of the project is reported below.

Julian Ferchow	PostDoc	Jan 23 - Dec 23	8%	CHART
Patrick Beutler	PhD	Jan 23 - Jul 23	100%	CHART
Aurel Schüpbach	PhD	Aug 23 – Dec 23	100%	CHART

4. References

[1] e. a. D. M. Araujo, «Subscale Stress-Managed Common Coil Design,» *", MT-28, submitted to IEEE Applied Superconductivity*, 2023.