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Advanced Manufacturing Techniques for Lightweight Muon Spectrometer Support Structures in the FCC Project

Jan Brajer (0009-0005-7705-9259)[1], Martin Dub (0000-0002-4027-0465)[1], František Lopot (0000-0001-5731-6784)[1], Pavel Malý (0000-0001-6370-2497)[1, 2]
[1]Faculty of Mechanical Engineering, Czech Technical University in Prague, 166 00 Prague. Czech Republic. E-mail: j.brajer@fs.cvut.cz, martin.dub@fs.cvut.cz, frantisek.lopot@fs.cvut.cz
[2]Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany. E-mail: pmaly@mpp.mpg.de

With the rising demand for efficient, lightweight support structures in high-energy physics experiments, advanced manufacturing techniques and material optimization are key to achieving high-performance designs. This study focuses on the application of generative design and topological optimization in the development of support structures for the FCC muon spectrometer. By leveraging these methods, we maximized material efficiency and minimized weight while ensuring structural integrity and meeting strict design constraints, including non-magnetic properties, minimal deformation, and high precision. A detailed evaluation was conducted with respect to manufacturing techniques that balance performance with cost-effectiveness, resulting in multiple design iterations of optimized truss configurations. This approach demonstrates the potential of modern manufacturing technologies in enhancing the structural and economic viability of components for large-scale scientific equipment.

Keywords: Additive Manufacturing, Topology Optimization, Generative Design, Muon Chambers, Detector, Frame, FCC

1 Introduction

Topology optimization and generative design are two main AI driven methods that help engineers to maximize the efficiency of material distribution, while maintaining the defined stiffness. While the end results of both of those methods are often very similar, they use very different process to achieve it, [1].

Both methods are undeniably very advanced and have proven to save time and resources, they however cannot be used without a supervising engineer who will revise and polish the final product.

Topology optimization is a mathematical method, which aims to determine the most efficient material distribution within an already defined model, that is aimed to be optimized usually to save material and/or weight. This method begins with a defined object that is then be divided into segments of defined size (mesh) and assigned all its properties. Once the object is meshed, is has then assigned all constrains. The next step is defining the performance objectives such as maximum deformation, pressure etc., [2, 3].

The process of the optimization itself consists of the algorithm testing each element using a mathematical method (for example finite element analysis) to determine tension in the element and its displacement. The algorithm then evaluates each node and iteratively redistributes material within the defined model, based on the defined objectives. The algorithm reinforces areas crucial for the performance and eliminates nodes that are insignificant for achieving target stiffness.

The final step is the post process and validation of the model generated by the optimization process. This process usually means adjusting the design to comply with required method of manufacturing and validating the iteration by further simulations, [4, 5].

Fig. 1 *Comparison on products manufactured by means of conventional and additive technology [6]*

Topology optimization design usually inclines into natural, bone-like structures (see Fig. 1), that can only be machined by very complicated means, or by using the additive manufacturing technology (FDM, SLS, SLM, ADAM etc.) [7, 8]. Problem also lies in stress distribution in those structures, which are anisotropic, therefore it is hard to analyticaly determine its mechanical properties [9]. Another issue lies in the inability of the topology optimization to create structures out of standard beam elements, so the post process can consist of re-creating the model out of industrial standard beams [10].

Although the model produced by the topology optimization process may seem perfect for the additive manufacturing on the first glance, it not unusually requires equal amount of post processing as the parts machined in conventional means. The main issue lies in the algorithm not considering the limits of the machine such as layers, maximum overhang angle and minimum wall thickness. Another issue is very complicated definition of various materials, that might not be isotropic due to the way the layers are added. Those factors are usually issue with polymers rather than metallic materials but make the utilization of the topology optimization way more complicated than it may seem, [11, 12].

2 Problem Description

Generative design and topology optimization is applied on the structure for Future Circular Collider (FCC) that should be as lightweight as possible while meeting prescribed design requirements, especially stiffness. The Future Circular Collider is a proposed particle accelerator project that aims to explore the frontiers of high-energy physics. It is being considered as a successor to the Large Hadron Collider (LHC), which is currently the world's most powerful and largest particle accelerator.

The FCC is designed to be an even more powerful and larger accelerator than the LHC, with the goal of reaching higher collision energies and enabling scientists to investigate new phenomena and particles that could provide further insights into the fundamental nature of the universe [13]. Designed structure is a part of the Barrel Muon System, see Fig. 2. The Barrel Muon System is a crucial component of the proposed Future Circular Collider (FCC). In particle physics experiments, muons are elementary particles that are created in high-energy collisions. The Barrel Muon System would be designed to detect and measure the properties of these muons in the FCC experiments.

The muon detection system in the FCC would be essential for studying a wide range of physics processes, such as the decay of the Higgs boson, the search for new particles or phenomena, and precision measurements of known particles. The Barrel Muon System would play a significant role in the identification, tracking, and precise determination of the energy and momentum of muons produced in these collisions.

The muon system typically consists of various layers or stations of detectors placed around the interaction region of the accelerator [14]. These detectors are designed to detect and track the trajectory of muons as they pass through the system. By measuring the curvature of muon tracks in magnetic fields, the system can determine the momentum of the muons and help identify specific particles and their decay products. It's important to note that the details of the Barrel Muon System, including its exact design and technology, would depend on the specific experimental goals and requirements of the FCC project. As the FCC is still in the planning and development phase, the precise specifications of the Barrel Muon System would be determined as part of the overall design of the collider [15].

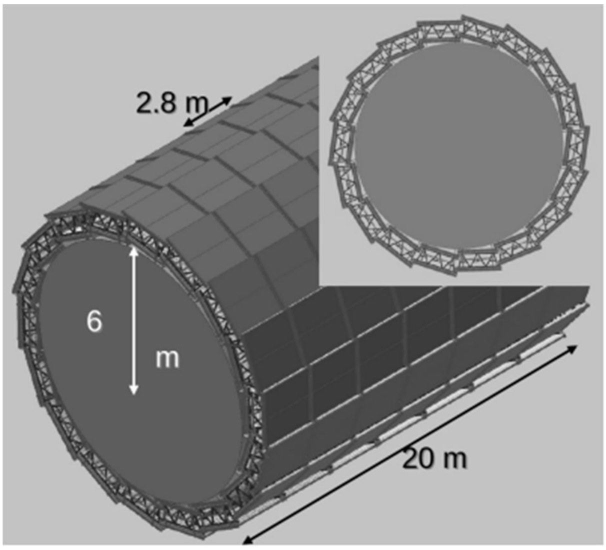

***Fig. 2** Conceptual design of the Barrel Muon System of FCC consisting of muon chambers [14]*

The scoped structure is to support of the muon chamber. The conceptual design is illustrated in Fig. 3. The muon chamber consists of the scoped structure with three anchoring points and muon tubes. The possible deflection of the muon tubes is limited due to the correct function. That is why the large stiffness of the supporting structure is necessary.

The first step for our project was defining the boundary conditions which were dictated by multiple factors, that all had to be considered.

The main constrains were defined by the anchoring points of the structure which also serve as lifting points during transport and installation, positions of the muon chambers and the surfaces used to attach them to the designed structure. The structure will operate in an environment with a stable temperature and humidity, so the only factors affecting the structure is the gravity and the load from the muon chambers attached to it.

The main requirement is its stiffness, defined by maximum deformation of 0.015 mm. The second is its ability to operate within all eight positions, achieving equal performance. For this purpose, different designs were introduced for each position. The support structure is loaded by means of self-weight and by means of the weight of the muon tubes. The weight of the muon tubes, which will be mounted on the top and bottom surface, is 140 kg together. This weight is distributed to the appropriate beams. The structure is supported in three anchoring points by means of the spherical hinges with possible longitudinal and lateral movements, so the structure is statically determinate (zero degrees of freedom).

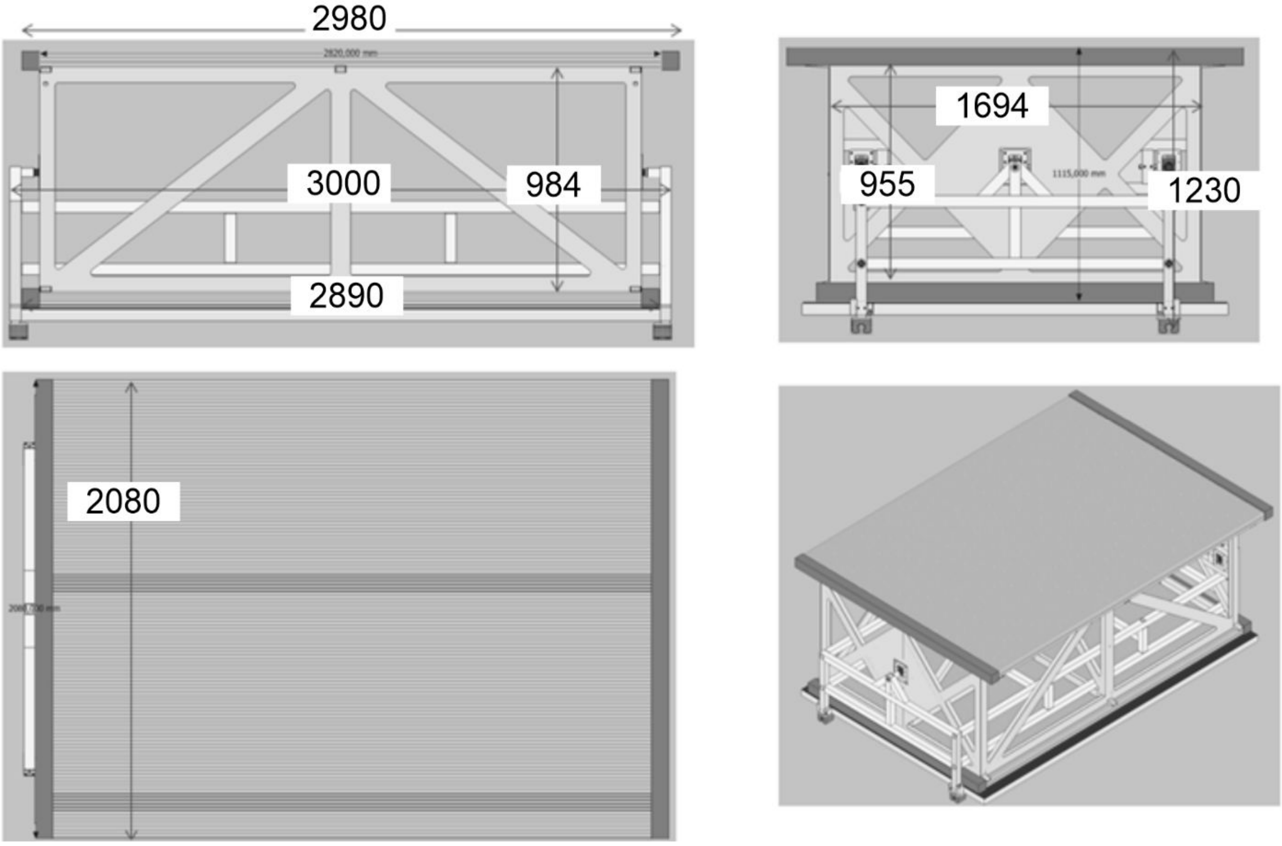

Fig. 3 *Conceptual design of the muon chamber support structure*

3 Generative Design

To achieve the first design of the support structure without any shape limitations except the limitations of the envelope, the generative design is used. It is used conventional software Autodesk Fusion. In Autodesk Fusion the material was set to aluminium alloy (AlSi10Mg) and the manufacturing method was unrestricted. That caused obviously, the additive manufacturing method is used. The target quantity in Autodesk Fusion can be set to maximum stiffness or minimum mass. It should be noted that generative design in Autodesk Fusion was used for preliminary design of the support structure.

The first variant is designed based on the initial geometry (Fig. 4) with target of minimum mass. The algorithm can design the structure in the yellow volume. The result structure can be seen in Fig. 5. The shape of individual beams are arbitrary so only additive manufacturing makes sense in this case. It can be seen, that in some cases the beams are interrupted, so that they lost their stiffness, and they are useless for the structure stiffness.

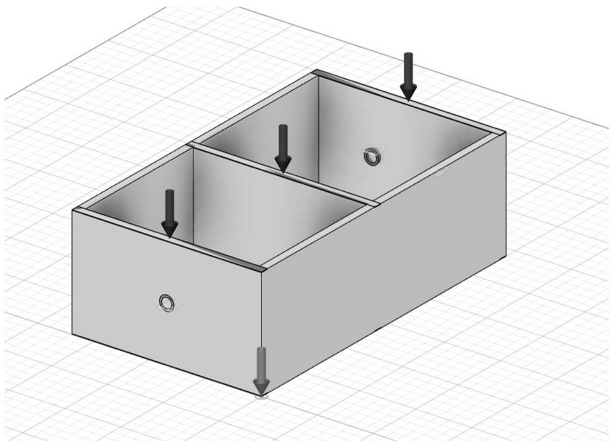

Fig. 4 *Initial geometry, loading and supports in Autodesk Fusion – first variant*

The second variant is designed without the initial geometry, only green volumes must remain (Fig. 6) with target of minimum mass. The result structure can be seen in Fig. 7. The shape of individual beams is arbitrary so only additive manufacturing makes sense in this case.

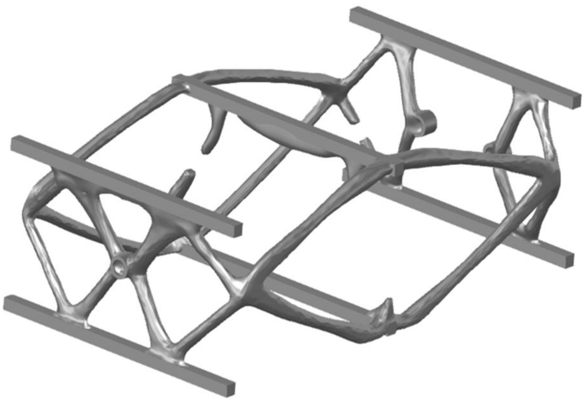

Fig. 5 *Result geometry – first variant: maximum displacement 0,809 mm; mass 382 kg*

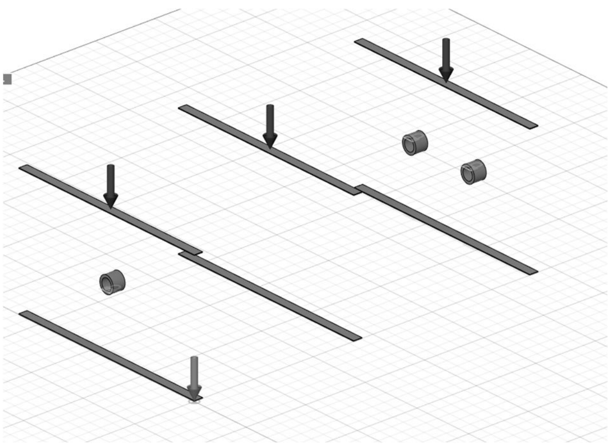

Fig. 6 *Initial geometry, loading and supports in Autodesk Fusion – second variant*

The third variant is similar to the second one, the difference is that the target quantity is the maximum stiffness. The result structure can be seen in Fig. 8. The shape of individual beams is arbitrary so only additive manufacturing makes sense in this case.

Obtained results are summarized in Tab. 1. All the designs are suitable only for the additive manufacturing and their shape must be further post processed. Furthermore, the target maximum displacement is met only in case of third variant. Due to inability of usage of hollow beams, the mass is also large in all three variants.

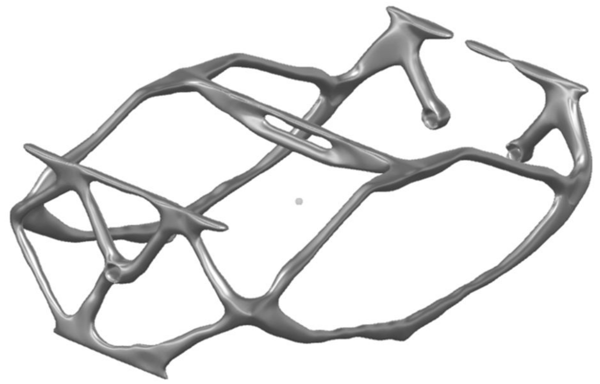

Fig. 7 *Result geometry – second variant: maximum displacement 1,407 mm; mass 288 kg*

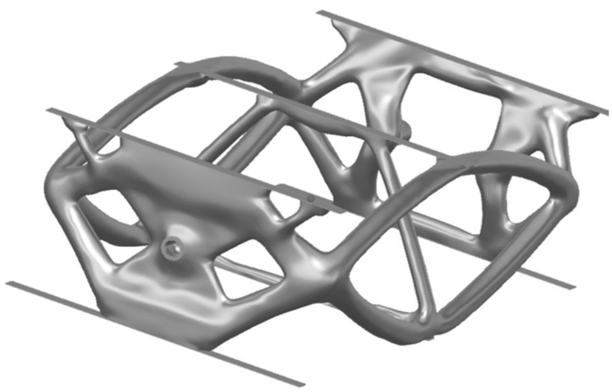

Fig. 8 *Result geometry – third variant: maximum displacement 0,018 mm; mass 797 kg*

Tab. 1 *Summary of generative designs results*

Variant	Maximum displacement [mm]	Mass [kg]	Description
1	0,809	382	Minimum mass
2	1,407	288	Minimum mass
3	0,018	797	Maximum stiffness

4 Topology Optimization

The tool used for the topology optimization was Ansys. This program allowed us to work with bodies as well as 1D beams, which allowed us doing all the steps of the iteration within it. The following steps do not consider the stiffness of the muon chambers themself to reduce the stress on them to the absolute minimum.

The dimensions of the outer envelope are 955 mm x 1694 mm x 2890 mm (H x W x D). To speed up the design process, two rectangular sections were removed from the large rectangular envelope. This step worked with a body type structure, consisting of a single body model, which allows the algorithm to reposition/remove nodes. For all the following steps, the 20 mm mesh was used. The anchoring points had free rotations around each axis. On one side, the displacements were restricted completely and on the other side, the anchoring point had displacement allowed in X axis direction and restricted in the rest. Those constrains were chosen in line with the definition of the anchoring points. This setup provides the most realistic deformation of the frame.

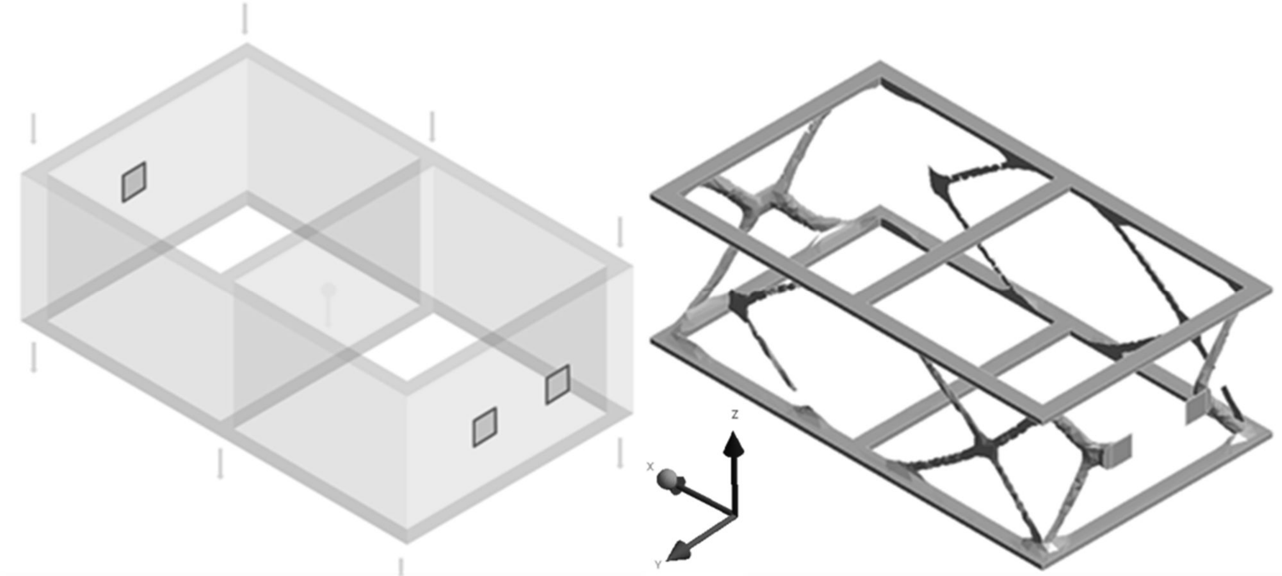

Fig. 9 *First iteration input and output model comparison*

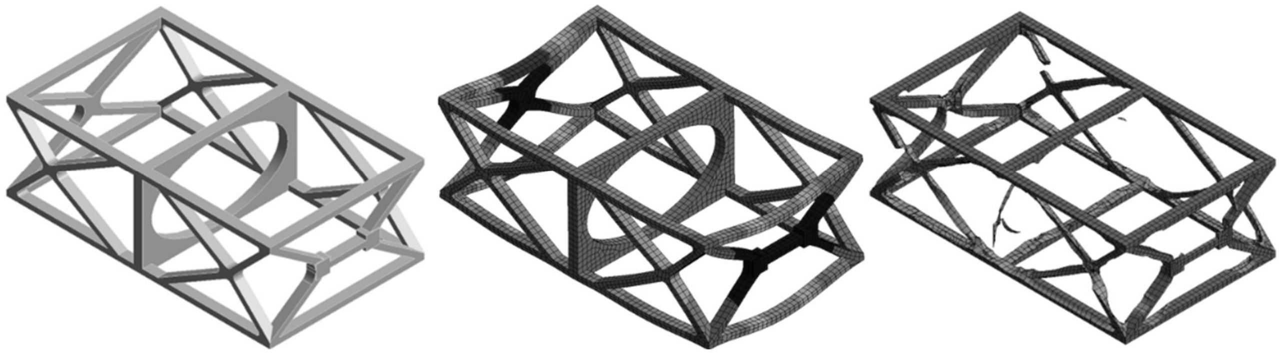

Fig. 10 *Second iteration input-output model comparison*

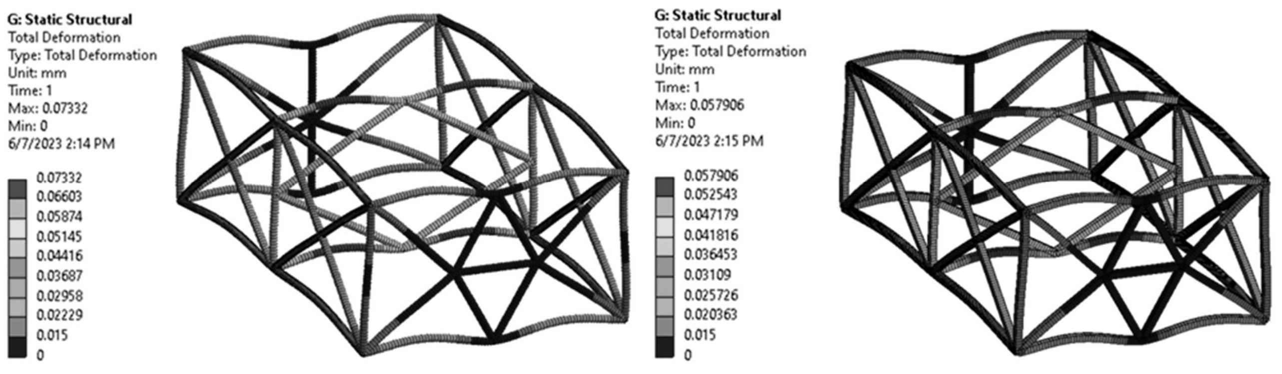

Fig. 11 *Beam structure composed of round profile 25x2 (left) and square profile 40x40x2 (right)*

The first iteration leads to massive weight reduction, however for further progress, a major remodelling is needed.

For the second iteration, the model was smoothened and fixed. The new model was then checked using a simulation. It was apparent from the results, that the model suits our needs, and a second optimization process was run on it.

The second optimization led to dividing the further development into two paths. One of them was focused on development of a structure with as high material distribution efficiency as possible, while the other one focused on a beam structure, based on the maximum cross section. The reason for this forking is the economical aspect of the project and issues with the manufacturing frame of this size.

For the following steps of the frame design, the 1D beam models were used. This method is very different to the solid body analysis. 1D models represent a time efficient and very versatile tool, that allows us to assign each beam its own properties. This method does not consider the beams as a solid body, but only as a beam with attributes attached to them. These speeds up the process of simulation and also provides the most precise data for this specific use.

Although the frame composed of circular beams is slightly lighter, it does not achieve nearly the same stiffness of the one composed of rectangular beams. The next step was defining the direction of the maximum deformation in order to distribute the material in the most efficient way.

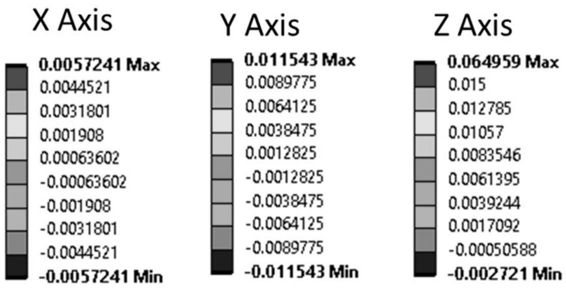

Fig. 12 *Directional deformation comparison*

As the fig. 12 implies, the maximum deformation occurs in Z axis and is caused by insufficient stiffness of the structure and the displacement of the middle plane.

In the current state of the project, the standard element structure is being further optimized and performances of different beams are compared.

The second path is currently on hold, due to difficulties in finding ways of manufacturing the structure.

5 Conclusions

In this article, we have introduced the construction of a muon chamber supporting structure for the Future Circular Collider (FCC) and how this design was developed based on the requirements for high rigidity. To achieve an optimal design, modern techniques of generative design in Autodesk Fusion and topology optimization in Ansys were utilized.

Generative design in Autodesk Fusion allowed the creation of various design variants for the chamber based on specified requirements and constraints. Obtained results are suitable for additive manufacturing technologies and need to be further optimized.

Subsequently, topology optimization in Ansys was performed, utilizing mathematical algorithms to identify and optimize the material distribution within the structure. This resulted in reducing the weight of the chamber while maintaining the desired rigidity and functionality. Obtained geometry was further manually transformed into the beam structure with hollow profiles to obtain structure manufacturable by means of conventional technology.

The outcome of these optimization processes is a muon chamber design for the FCC that can meet the requirements for high rigidity while being optimized in terms of weight and manufacturing costs. This design is the result of combining modern design techniques and simulation tools that enable efficient development and optimization of technical systems.

In the future, these proposed design methods could be utilized in the realization of muon chambers for the FCC and other similar projects. Their application allows for efficient and optimized design that meets technical requirements while minimizing costs and material resources.

Overall, the proposed muon chamber design for the FCC based on generative design in Autodesk Fusion and topology optimization in Ansys represents progress in the field of design and optimization of technical systems.

Acknowledgement

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References

[1] KENAN TAŞ, DUMITRU BALEANU, J. A. TENREIRO MACHADO (2019). Mathematical Methods in Engineering, *Springer Cham*.

[2] MAREŠ, T. *Základy Konstrukční Optimalizace* [online]. Sv. 2. Prague: Self-funded, 2006.

[3] G.I.N. ROZVANY. "A critical review of established methods of structural topology optimization."Struct. Multidisc. Optim. *Springer-Verlag* 2008.

[4] DHEERAJ GUNWANT AND ANADI MISRA, (2012), "Topology Optimization of sheet metal brackets using ANSYS". MIT *Int. J. of Mech. Eng.*, Vol. 2. No. 2.

[5] D. BRACKETT, I. ASHCROFT, R. HAGUE. *Topology optimization for additive manufacturing*, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK ENNOMOTIVE. *Rapid Prototyping with 3D Printing and Additive Manufacturing*. Available online: https://www.ennomotive.com/beyond-rapid-prototyping-with-3d-printing// (accessed 14 November 2024).

[6] MATUŠ, M., BECHNÝ, V., JOCH, R., DRBÚL, M., HOLUBJÁK, J., CZÁN, A.,

NOVÁK, M., SAJGALIK, M. (2023). Geometric Accuracy of Components Manufactured by SLS Technology Regarding the Orientation of the Model during 3D Printing. *Manufacturing Technology*. 23. 10.21062/mft.2023.027.

[7] CZAN, A., CZANOVA, T., HOLUBJAK, J., NOVAK, M., CZANOVA, N., CZAN, A., KRISAK, D. Analysis of the Basic Characteristics of the Working Accuracy of the Atomic Diffusion Additive Manufacturing ADAM Process by Comparison with the Selective Laser Melting SLM Process. *Manufacturing Technology*. 2024;24(1):15-27. doi: 10.21062/mft.2024.015.

[8] SAPIETA, M., ŠULKA, P., SVOBODA, M.: Using a numerical model to verification of thermoelastic analysis of flat specimen, In: *Manufacturing Technology*, Vol. 18, No. 3 (2018) pp 482-486, ISSN: 1213-2489, DOI: 10.21062/ujep/125.2018/a/1213-2489/MT/18/3/482

[9] JÁNOS PLOCHER, AJIT PANESAR, Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures, *Materials & Design*, Volume 183, 2019, 108164, ISSN 0264-1275,43-974X

[10] SVOBODA, M., SOUKUP, J., PETRENKO, A.: Use of FEM Programs in Solving General Unbalance Simple Mechanical System, In: *Applied Mechanics and Materials*, vol. 732 (2015), p. 275-282. Trans Tech Publications, Switzerland, 2015, doi: 10.4028/www.scientific.net/…275

[11] ČERNOHLÁVEK, V., SVOBODA, M., ŠTĚRBA, J., CHALUPA, M., SAPIETA, M.: Analytical and experimental solution of vibrations of a system of bound bodies, In: *Manufacturing Technology*, Vol. 20, No 6 (2020) , pp. 699-707, ISSN: 1213-2489, DOI: 10.21062/mft.2020.116

[12] The FCC Collaboration (2019). FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3. *European Physical Journal Special Topics*, 228(4), 755-1107.

[13] VON BOEHN-BUCHHOLZ, R ; PODKLADKIN, S ; TCHEPOURNOV, V ; WOTSCHACK, J,. *Conceptual design of the ATLAS EM muon chamber support structures*, 1998. - 31 p., 2 Apr 1998. - 31 p.

[14] KORTNER, O., KORTNER, S., KROHA, H., PODKLADKIN, S., RICHTER, R. (2019). Design of the FCC-hh muon detector and trigger system. Nuclear Instruments and Methods in Physics Research. Section A: Accelerators, Spectrometers, *Detectors and Associated Equipment*. Volume 936. 2019. Pages 447-448.