Optimization of Strut Diameters in Lattice Structures

S. Teufelhart*, G. Reinhart*

*Fraunhofer Institute for Machine Tools and Forming Technologies (IWU),
Project Group for Resource-Efficient Mechatronic Processing Machines (RMV)
86153 Augsburg, Germany

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Abstract

Additive manufactured lattice structures show a high potential for lightweight design. Currently, these structures have a periodical build-up, which leads to disadvantageous stress states. On the one hand, unfavorable bending loads on the single struts appear. This can be avoided by an adaption of the course of the structure to the main stress directions inside the part. On the other hand, different stress values are appearing inside the single struts. Therefore, a procedure for the optimization of the struts diameters is presented. Thus, it becomes possible to achieve equal stresses in the whole structure and gain a better lightweight performance.

Introduction

Currently, an increasing spreading of Additive Layer Manufacturing (ALM) process is recognizable in industry [1]. One reason for this tendency is the high process flexibility and the possibility to produce parts with a high geometric complexity [2]. Beyond that, in the last years the application range of SLM processes has extended from manufacturing of prototypic parts to the production of applicable technical components, as well as from the processability of plastics to the generation metal components [3]. This offers great opportunities for the manufacturing of lightweight components and function integrated parts. Possible approaches for lightweight design can be classified corresponding to their geometrical dimension [4]:

- microscopic (greek: small) approaches: variation of the materials microstructure in dependence of the respective requirements of the part; e. g. well-directed build-up of porous material
- mesoscopic (greek: middle) approaches: adaption of the structure of the material; e. g. replacement of massive part areas by filigree structures like honeycombs or lattice structures
- makroscopic (greek: big, wide) approaches: adaption of a parts material with respect to emerging loads; e. g. topology optimization based on the finite elements method (FEM)

The mesoscopic lattice structures are main focus of the paper. In the currently established approach for their application, these structures have a periodic design. Several software tools for the generation of such geometries for Additive Layer Manufacturing are already available. However, this kind of structure is not ideal, because they do not apply the whole potential of this approach for lightweight design. The reason for that is that in periodic structures a great amount of bending loads appear and the stresses in the single struts are not equal [5]. This state is not the optimal constitution for lightweight design. Rather, only push and pull forces should appear inside the single struts and the load should be equal for the whole structure.

Recent Approaches for the Optimization of Lattice Structures

For the optimization of the design of lattice structures, some few approaches have been presented in the past. Some of them deal with the optimization of the build-up of frameworks, which is quite similar to the geometrical more filigree lattice structures; and some deal with the optimization of the densities of lattice structures. The most important of the latter ones will be introduced in the following section to illuminate their usability for flux of force adapted structures.

In [6], the influence of different parameters on the properties of lattice structures has been investigated. Therefore, a torsion-loaded hollow shaft has been build up of a helix shaped lattice structure, and different parameters, like the angle of the helices relative to the torsion axis, the struts diameters and the number of struts in each direction, have been varied. The results have been compared by the ratio of the shaft's torsion stiffness to its mass. It has shown that the ratio had the best values if the struts were orientated along the flux of force, and if all of the struts were loaded with the same stress. In case of a torsion loaded hollow shaft, it is quite easy to reach this state because the stress conditions are almost equal all over the part. However, for more complicated parts where the structure cannot be described by few parameters, another proceeding has to be developed.

In [7], the most acknowledged calculation model for the strength of metallic cellular materials has been developed. The presented considerations are derived from assumptions of cell deformation and failure. Thus, a first approach for the calculation of the compressive strength of open-cell lattice structures was derived. It has shown that the presented approach is suitable until relative densities up to 0.3.

Rehme [8] carries out further investigations on the mechanical behavior of cellular structures. He expands the presented approaches in [7] for relative densities above 0.3. Furthermore, he takes the anisotropic material behavior of additive manufactured solids and lattice structures into account. The investigations are of theoretical and experimental nature. For the latter ones, the producibility of the structures by additive manufacturing processes is also addressed.

Both, the approach of Gibson and Ashby [7] as well as the approach of Rehme [8] are working with a homogenized material model of the in fact inhomogeneous lattice structures. This is feasible for the regarded periodic structures. However, for flux of force adapted structures with varying densities, as we can find them in the presented project, this approach cannot be utilized.

For this reason, after a brief overview of the optimization procedure for flux of force adapted lattice structures, a necessary differing approach will be presented, which regards the structure as single struts.

Procedure for Load-dependent Optimization of Lattice Structures

In [9], a proceeding for the load-dependent optimization of lattice structures has been introduced. Thereby, the optimization regards two main aspects. On the one hand, the course of lattice structures is getting adapted to the flux of force inside the respective part. This has the effect, that bending loads on the single struts can be avoided or at least strongly reduced, which has a positive effect on the part's properties concerning lightweight design. On the other hand, the geometries of the single struts and the nodes in the structure are optimized with respect to their loads. The general proceeding for these optimizations can be seen in Fig. 1.

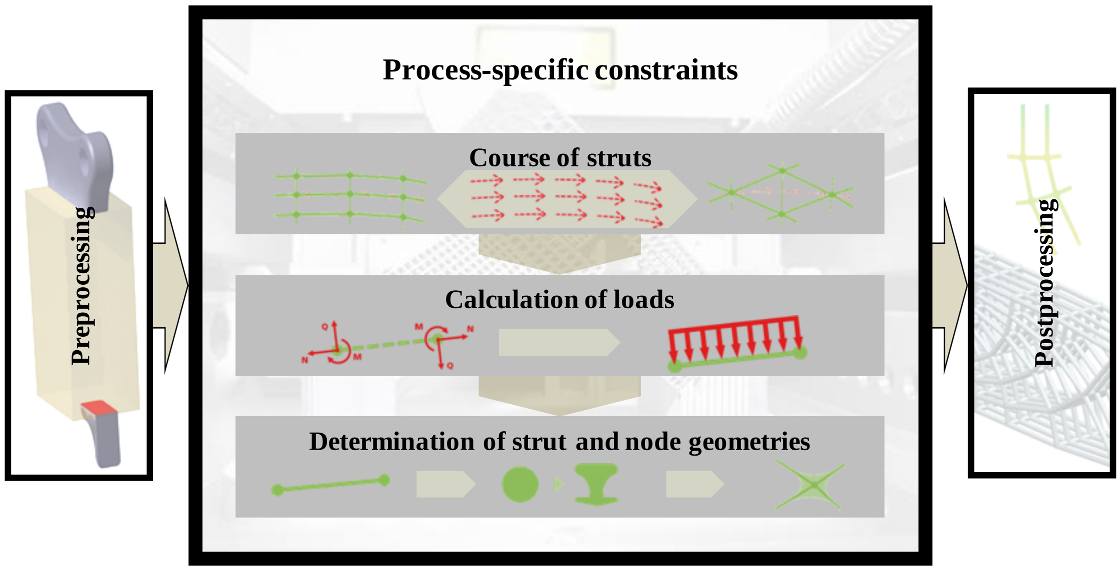

Fig. 1: Proceeding for the load-adapted optimization of lattice structures, according to [9]

The optimization is realized with the software NX by Siemens and its integrated NASTRAN solver. Therefore, several algorithms were written in MATLAB and NXOpen, which is the corresponding programming language for NX. Anyway, the optimization can also be done with other CAE systems and calculation programs. However, for the presented project, NX has been chosen because it provides all of the needed CAE tools and it is comprehensively programmable with NXOpen.

The optimization process begins with the preprocessing of the optimization data. Here, the design-space for the optimization, as well as component parts which will not be optimized in the later optimization procedure (e. g. for force application, screw treads or bearing carriers), are modeled in a CAD system. For this geometry, a finite elements model is generated, which contains all of the constraints and loads for the later structure. The model is solved and the solver output data is used for the following build-up of the structure.

The optimization is executed under consideration of the process-specific constraints, which arise from the used additive manufacturing process. Hereunto, numerous investigations for the material AlSi12 have been done in the past. Therefore, extensive tensile tests have been carries out in order to determine the dependencies of the manufacturability of the single struts and their mechanical properties from several parameters like build-up angle, strut length and strut diameter. The results have been integrated in an anisotropic, geometry-dependent material model which describes these correlations. This model is used in the following optimization process for the orientation of the structure as well as the optimization of the struts diameters. [10]

The optimization process starts with the flux of force dependent build up of a basic structure. Therefore, the flux of force in the design space has to be determined, which is executed based on the solver data from the preprocessing. For this purpose, the main stress directions for each element respectively node is calculated. With the help of these vectors, a sequence of points can be determined, which represent the flux of force respectively the main stress curves. The intersection points of these curves characterize the nodes for the later lattice structure. When all of these nodes have been constructed, straight beams are located between the respective correlating nodes (compare Fig. 3) [11]. Unfortunately, this build-up process of the three dimensional structure from the lines for the flux of force still needs high manual effort. Therefore, in future works, an automated algorithm will be developed, which executes this task and reduces human interaction.

For the resulting structure, suitable diameters for the struts have to be found, which fulfill predefined requirements like maximum stresses or minimum diameters. The proceeding for this optimization is the main content of this contribution and will be described in the following sections. In addition to that, the material model, which was mentioned before, will be integrated into the optimization of the diameters in order to incorporate the anisotropic, geometry-dependent material behavior in the optimization.

Besides the geometry of the struts, the design of the single nodes has to be optimized, too. A smooth merging between the single struts in the nodes has to be realized to avoid high notch stresses (see Fig. 13). A suitable design of these nodes, as well as an automated algorithm to realize them in 3D CAD systems respectively finite elements systems (here Siemens NX) will be developed in future works.

In the postprocessing, the optimized structure has to be made applicable for subsequent processes. Therefore, a 3D CAD model can be build up for further design steps or data processing for the following manufacturing of the optimized structure. A respective NXOpen program has been developed in the past to perform this task.

Results for the Optimization of the Course of Lattice Structures

In [5], lattice structures, which are adapted to the flux of force inside a respective part, are compared to a structure with a regular build-up. For that purpose, a design space with constraints and forces as depicted in Fig. 2 is used as initial situation for the respective optimizations.

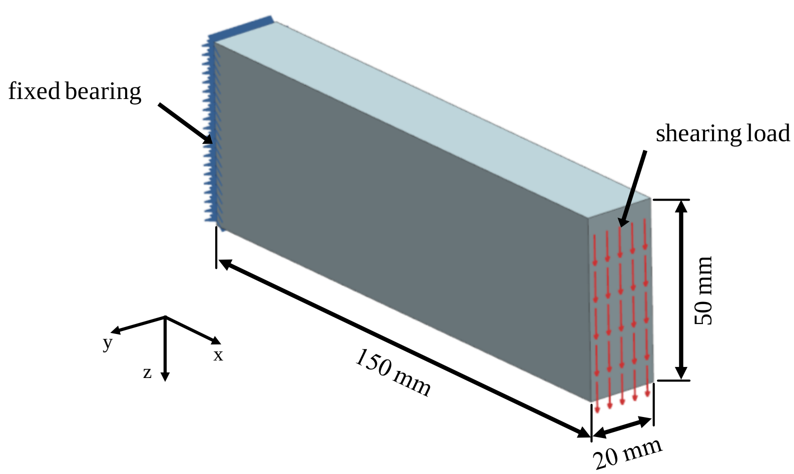

Fig. 2: Design space, constraints and load for optimization, according to [5]

The material used for the investigations is aluminium 6061 without thermal treatment, which has the following mechanical properties:

- Young's modulus: 58.1 GPa
- Limit of elasticity: 55 MPa
- Tensile strength: 125 MPa
- Density: 2.711 g/cm³

The strut diameter for all structures is kept constant at 2 mm, because only an adaption of the course of the lattice structure should be considered.

In the investigations, the maximum von-Mises comparison stress is determined in order to rate the stability of the particular structures. It is assumed that the maximum stress linearly depends on the applied force on the structure. Hence, the force at the limit of elasticity can be calculated. The ratio of this load to the respective mass is used to compare the different structures, whereat a higher ratio indicates a better lightweight design.

Initially, a periodic structure build-up is investigated. This is the currently established approach for the application of lattice structures in lightweight design. The structure has a total mass of 147.5 g. The corresponding maximum value for the von-Mises stress is 50.58 N/mm². Under the assumption, that this maximum stress linearly depends on the applied force, a maximum load of 406.6 N can be calculated for the obtaining of the limit of elasticity. The ratio of this force to the part's mass is 2.76 N/g. This value is used in order to compare the structure with the other ones in the paper.

Another structure, which is presented in [5], is adapted to the flux of force in the design space (see Fig. 2). Here, the single nodes of the structure are located along the fluxes of force in main stress direction 1, 2 and 3. These nodes are connected by straight struts to build up a structure. This build-up has the advantage that almost no bending loads appear on the single struts. Analogue to the investigations presented before, the diameters of the struts is set constant to 2 mm.

The resulting structure and its constraints and loads can be seen in Fig. 3. The mass of this geometry is 83.58 g. Thus, the weight is 43 % less than with conventional periodic structures.

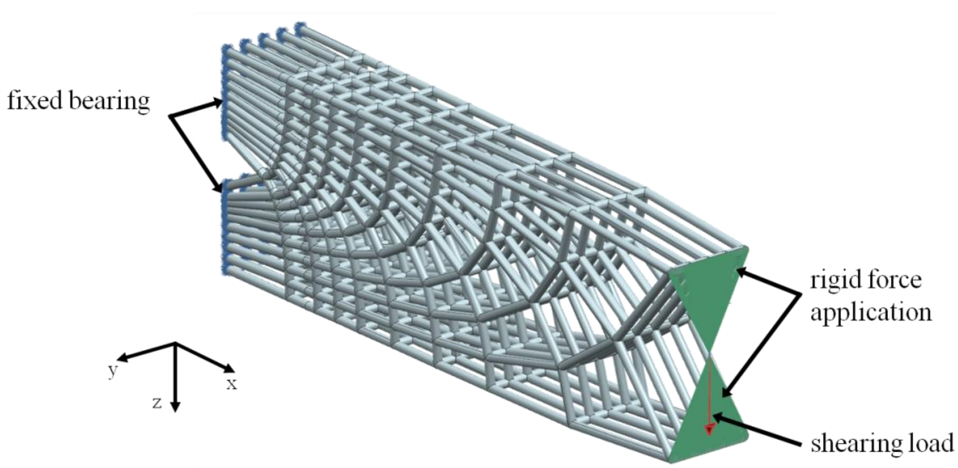

Fig. 3: Shear loaded beam with flux of force adapted lattice structure [5]

The resulting maximum von-Mises stress is 31.9 N/mm². Under the assumption that this maximum stress linearly depends on the applied force, a maximum load of 516.8 N can be calculated for the obtaining of the limit of elasticity. For the resulting ratio of this force to the structure's mass, a value of 6.18 N/g can be calculated. Hence, the ratio has increased for 124 % compared to the periodic structure.

Thus, it can be summarized that the adaption of the structure's course to the flux of force in the design space has a great potential for lightweight design. This is grounded in the fact that almost no bending loads appear for this kind of structure. [5]

Uniform Optimization of Strut Diameters in Lattice Structures

The results of [5], which have been presented in the section before, have been determined for the arbitrary chosen diameter of 2 mm. However, to reach a predefined maximum von-Mises stress or displacement, additional investigations have to be done. In the following section, such calculations are presented for a beam, which is similar to the one presented before.

For this purpose, the structure is built up with 1D CBEAM elements and the strut diameters are varied uniformly for the whole structure. The influence of these strut diameters on the mechanical properties, in this case the maximum von-Mises stress, is determined. The results of these investigations can be seen in Fig. 4.

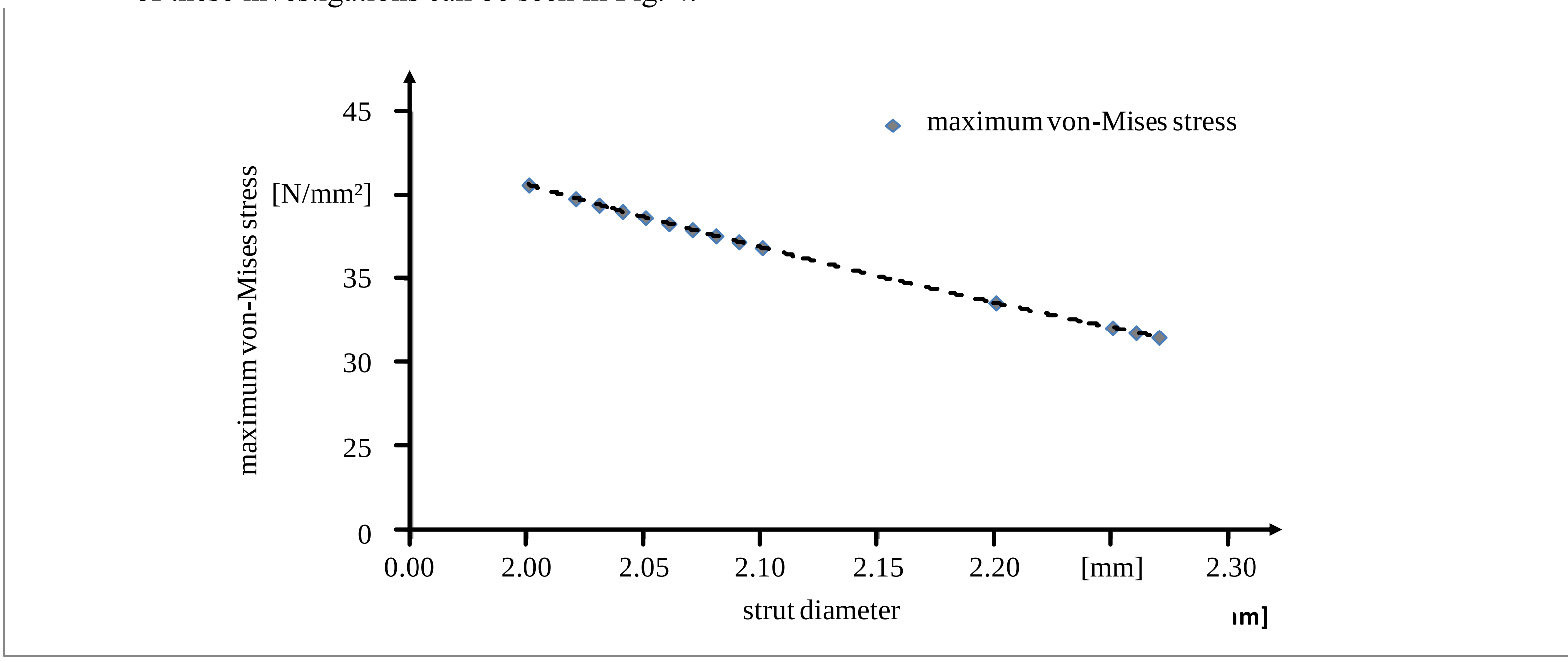

Fig. 4: Maximum von-Mises stress in dependence of the struts diameter

Because almost solely push and pull forces appear on the struts, the maximum von-Mises stress is indirectly proportional to the cross sectional area and thereby indirectly proportional to the squared diameter.

For this and the following example, the optimization goal is set to a maximum von-Mises stress of 32 N/mm². This result is used for strut diameters of 2.26 mm, which means a mass of 104 g for the structure. In combination with the maximum von-Mises stress of 31.8 N/mm² and the force at the limit of elasticity of 518.4 N, a ratio of force to mass of 4.97 N/g can be calculated. This structure will also be the basis for the optimization of the single strut diameters in the following section.

Optimization of Strut Diameters in Lattice Structures

Beyond the optimizations of the course of lattice structures and the uniform optimization of the struts diameter, the cross section of the single struts can also be varied independently of each other. Thereby, a constant material saturation can be reached within the part, which leads to an enhanced lightweight design. The computer based proceeding for this optimization can be seen in Fig. 5.

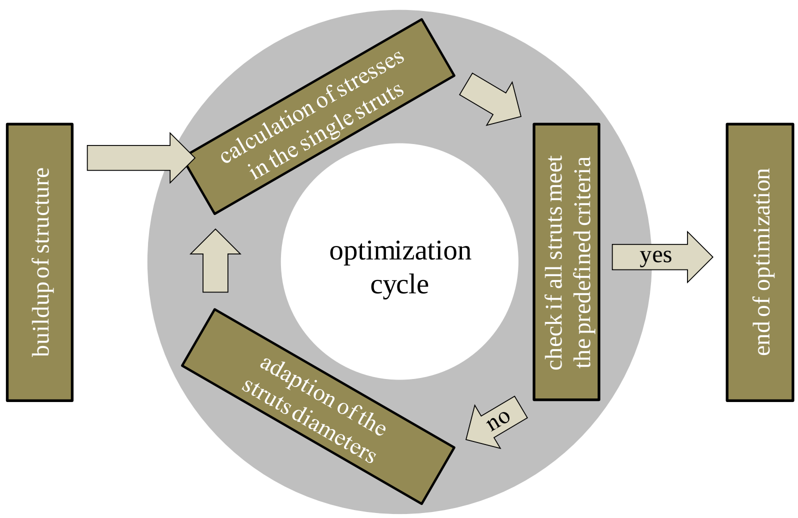

Fig. 5: Proceeding for the optimization of the strut diameters in lattice structures

The optimization starts with the automated build-up of the initial structure by a macro for the CAE software NX from Siemens. Therefore, the nodes are placed along the flux of force as described before. These points are connected with 1D CBEAM elements which are described by the corresponding nodes and the respective diameters of the circular cross sections. Furthermore, the occurring constraints and loads are applied on the structure.

When the initial structure is completed, the actual optimization circle starts. Here, the van-Mises stresses in the struts of the initial structure are calculated. Subsequently, the algorithm checks if all struts meet the predefined exit conditions (e. g. designated stress, minimum diameter). In the case that this is true, the procedure stops and the optimization has finished. If not, the struts diameters are adapted in dependence of the designated stress and the respective appearing stresses. Therefore different functions can be applied, which has an influence on the optimization time. For the resulting structure, the stresses are calculated again and the cycle starts over, until all struts meet the exit conditions.

This optimization procedure has been applied to the structure, which has been presented before for a shear loaded beam (see Fig. 3). For this purpose, the structure has been build up with CBEAM elements, which have fixed connections among each other in the respective nodes. For the optimization, a target von-Mises stress of 31-32 N/mm² as well as a minimum strut diameter of 0.5 mm have been set as exit condition. The resulting structure can be seen in Fig. 6.

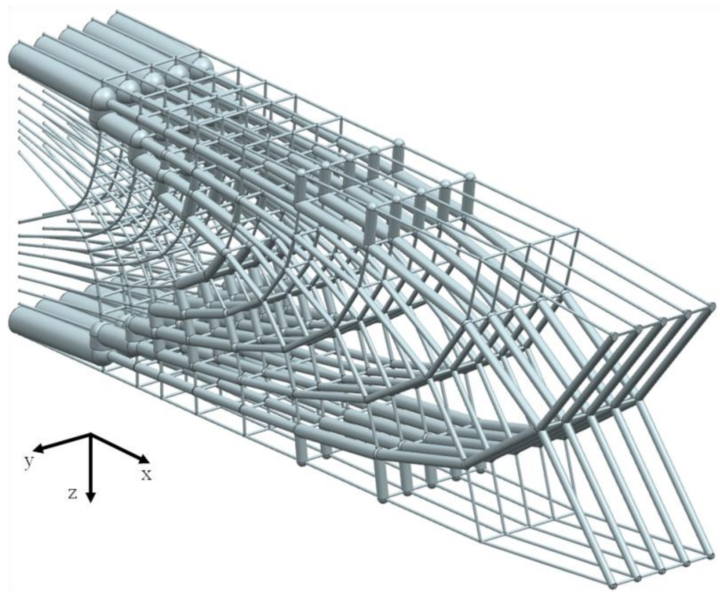

Fig. 6: Structure which was optimized with fixed nodes and a maximum von-Mises stress as optimization goal

The result is a very inhomogeneous structure. There are local areas with very thick struts, while the there is almost no material behind these areas. The reason for this behavior can be found in inappropriate stress states while the optimization cycle. Here, bending loads can appear on single struts due to the deformation of the loaded structure, which leads to stress peaks. Since the new diameters are calculated on the basis of this maximum stress, these struts are growing disproportionately high. This leads to reduced loads on the struts behind these massive areas so that these struts are getting more resilient. Thus, the thick beams are loaded even more. As a result, the thick struts are getting thicker until they reach the maximum acceptable von-Mises stress. At the same time, the thin struts are getting thinner until they reach the minimum acceptable diameter.

The resulting distribution of the von-Mises stress in the structure can be seen in Fig. 7. The structure has a mass of 106 g and a maximum stress of 31.38 N/mm². The force, at which the limit of elasticity is reached for this structure, is 525.8 N. From these values, a characteristic coefficient of 4.960 N/g can be calculated for the ratio of load capacity to mass. This even means a minor worsening compared to the initial structure. The reason for that can be found in the increased appearance of bending loads on single struts due to the unfavorable diameters.

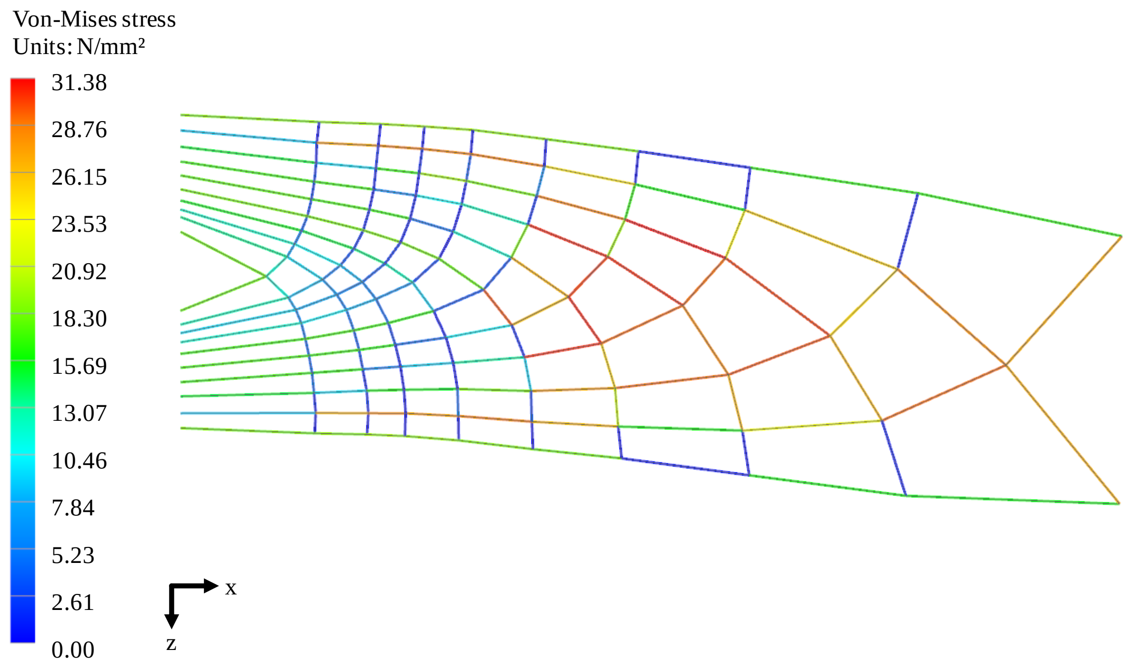

Fig. 7: Von-Mises stress in a structure which was optimized with fixed nodes and constraints and a maximum von-Mises stress as optimization goal

Furthermore, it can be seen that the distribution of the stress over the structure is very inhomogeneous. Ideally, most of the struts should show a similar stress near the designated value (here 31.0-31.9 N/mm²).

Therefore, an alternative approach for the optimization of the diameters has to be found, which is not negatively influenced by the bending loads on the single struts while the optimization cycle. To reach a stress state, which does not show any bending loads inside the structure, the rotational degrees of freedom (DOF 4, 5 and 6) at the connection nodes between the beams are released, as well as the respective degrees of freedom in the constraints. Thus, moments can no longer be transmitted which avoids the appearance of bending loads.

This proceeding is feasible for a first optimization step, because ideally, there should not appear any bending forces in the flux of force optimized structure, anyway. However, a subsequent calculation of the strut loads with fixed DOFs in the constraints and nodes is necessary after the optimization. The results for the optimized structure can be seen in Fig. 8.

As it can be recognized, the structure shows a way smoother distribution of the struts diameters. Here the forces are transmitted along the strut courses from the force application points to the constraints. This leads to a reduced mass of 58.1 g for the structure.

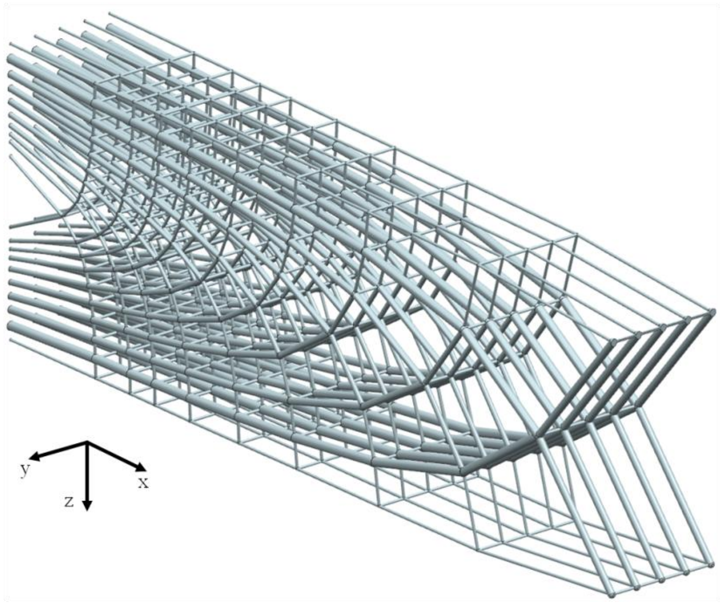

Fig. 8: Structure which was optimized with released rotational degrees of freedom at the nodes and constraint and a maximum von-Mises stress as optimization goal

The resulting von-Mises stresses for this structure can be seen in Fig. 9.

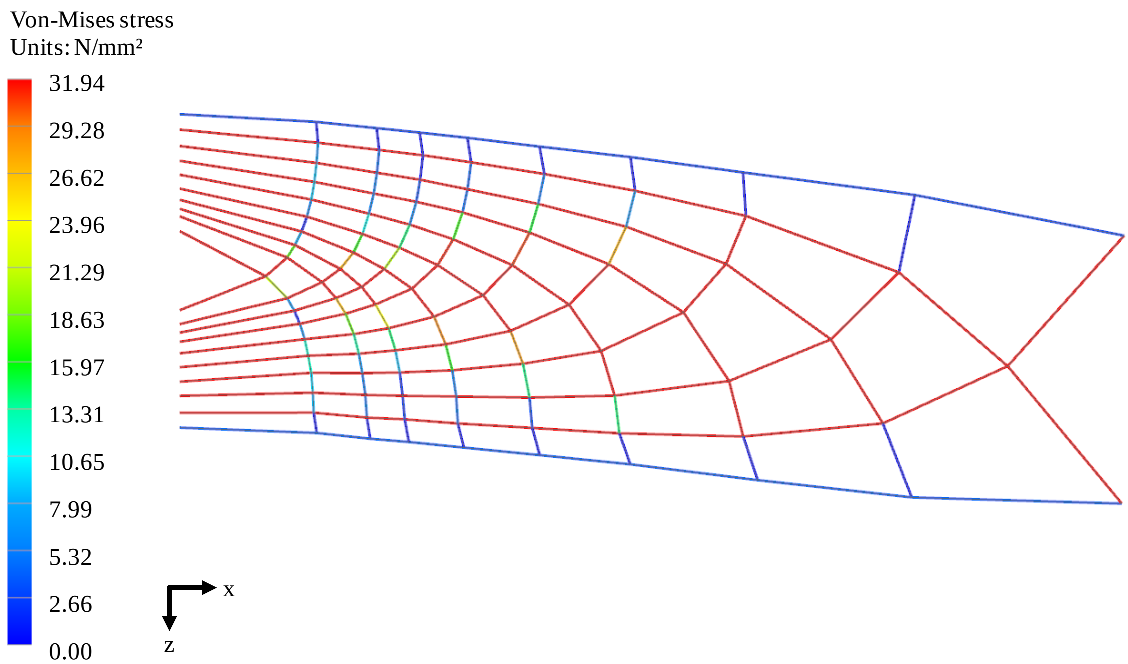

Fig. 9: Von-Mises stress in a structure which was optimized with released nodes and constraints and a maximum von-Mises stress as optimization goal

As it can be seen, the resulting distribution of the stress over the structure is way more homogeneous than for the optimization presented before, which indicates a good lightweight design. Most of the struts meet the predetermined stress values. The remaining struts are restricted by the minimum diameter of their cross section.

Hence, a maximum von-Mises stress of 31.94 N/mm² appears in the structure. The force, at which the limit of elasticity is reached for this structure is 516.6 N. From this value, a characteristic coefficient of 8.891 N/g can be calculated for the ratio of load capacity to mass. This means an enhancement of 79 % compared to the structure presented before and to the initial structure. The reason for that can be found in the strongly reduced appearance of bending loads on single struts and the way more uniform distribution of the stress in the structure.

However this proceeding leads to a problem concerning the automated optimization of the struts diameters. Since the system is underdetermined if all rotational degrees of freedom are released, single minor loaded DOFs have been fixed manually to reach a statically determined state of the structure. Otherwise, the solver cannot calculate the model and the corresponding finite elements software produces an error. However, because the optimization procedure is meant to work automated for complex structures, this manual interaction is not suitable.

For this reason an alternative approach for the optimization has been developed, which also is not negatively influenced by bending loads on the single struts, but – in contrast to the preceding approach – does not need any manual interaction.

To explain this alternative proceeding, the stress conditions in beam elements for the used NASTRAN solver have to be explained. For beam elements, the calculation of the stresses is executed at four characteristic points, the so called stress recovery points (C, D, E and F, see Fig. 10).

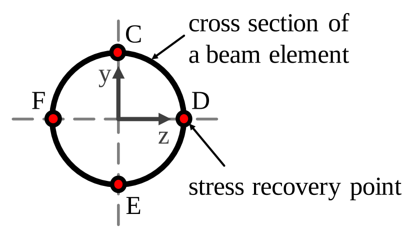

Fig. 10: Stress recovery points (C, D, E and F) at the ends of beam elements for a NASTRAN solver

The push respectively pull part of the combined load in a beam element can be determined out of the points stresses by calculating their average value. If this average stress is used for the optimization of the struts diameters instead of the maximum value, the bending loads do no longer have an influence on the result. Hence, an optimized structure as presented before can be achieved without manual interaction. The result from this optimization approach can be seen in Fig. 11.

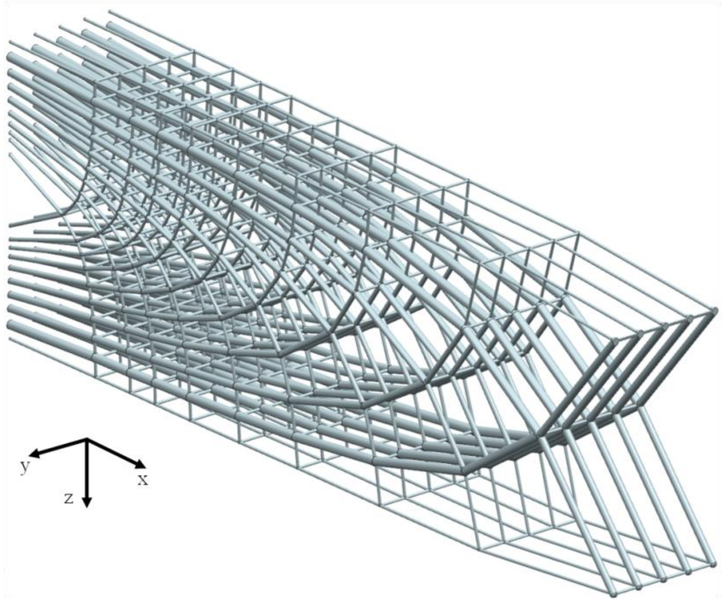

Fig. 11: Structure which was optimized with fixed rotational degrees of freedom at the nodes and constraints and an average von-Mises stress as optimization goal

As before, the structure shows a smooth distribution of the struts diameters. This approach leads to a comparable mass of 57.5 g. The maximum von-Mises stress is comparable as well with a value of 31.95 N/mm² (see Fig. 12).

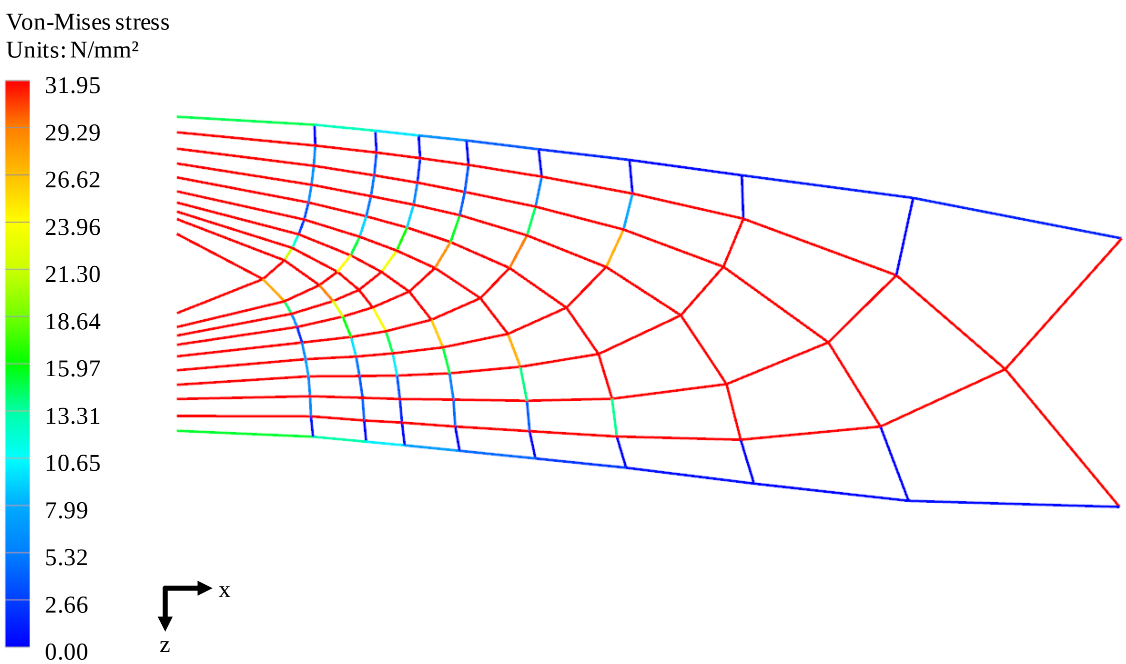

Fig. 12: Von-Mises stress in a structure which was optimized with fixed nodes and constraints and an average von-Mises stress as optimization goal

Hence, a proceeding for optimization of the struts diameters has been developed, which works without manual interaction for flux of force adapted structures.

In structures which are not adapted to the flux of force, however, bending loads do appear in the struts. Therefore, the last two proceedings do not work. Here, the first procedure has to be adopted. The optimization results for the investigated structures are summarized in Table 1.

	mass [g]	von-Mises stress [N/mm²]	force at limit of elasticity [N]	maximum force / mass [N/g]
uniform diameter	104	31.83	518.5	4.97
fixed nodes; maximum stress	106	31.38	525.8	4.96
released rotational DOFs; maximum stress	58.1	31.94	516.6	8.891
fixed nodes; average stress	57.5	31.95	516.4	8.981

Table 1: Summary of the properties of the investigated structures

In Fig. 13, a 3D simulation of the structure can be seen, which has been optimized with fixed nodes and constraints and an average von-Mises stress as optimization goal. Comparable to Fig. 12 with beam elements, it is recognizable, that the stresses in the struts are almost equal all over the structure.

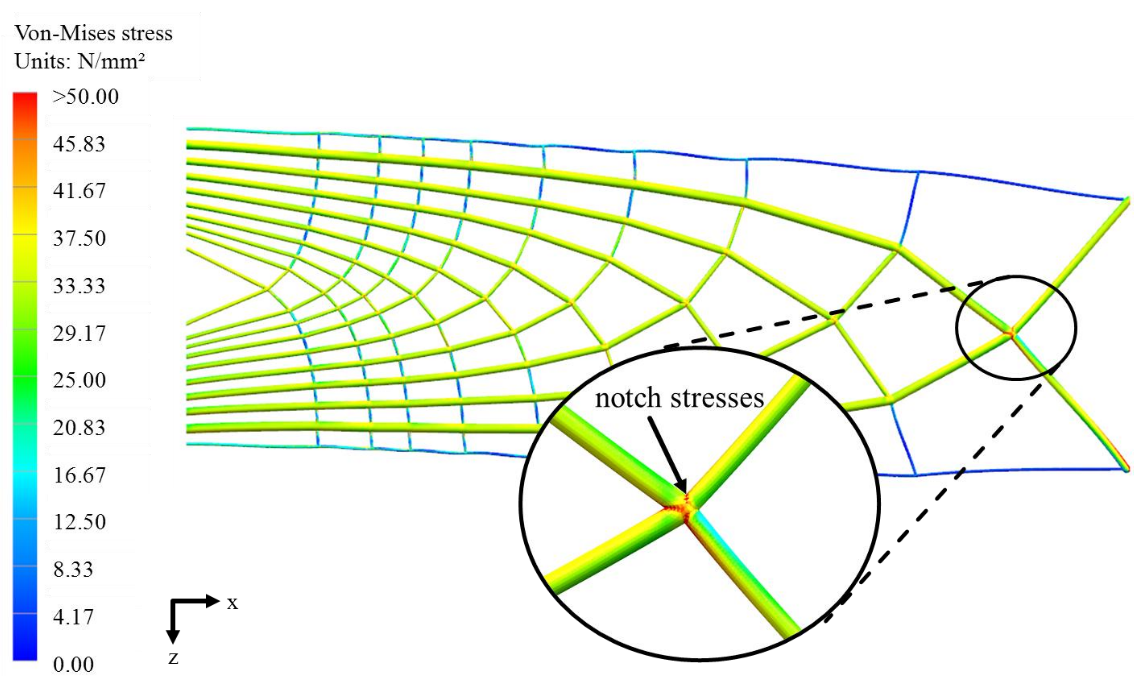

Fig. 13: Simulation of the optimized structure with 3D elements

However, there do appear notch stresses in the nodes where the struts are connected. Therefore, in future works there has to be found a better design for the nodes, where the struts merge smoother and therefore no notch stresses appear.

Summary and Outlook

It has been exemplified that Additive Layer Manufacturing has a great potential for the production of lightweight components. Especially mesoscopic approaches like lattice structures exhibit great properties for mass reduction. However, these structures are currently designed as periodic patterns. This leads to unfavorable bending loads in the single struts and uneven stresses over the structure.

To improve the structures build-up, an optimization approach has been introduced, which adapts the course of the structure to the flux of force in a part. The great potential of this proceeding has been shown at the example of a shear loaded beam. Here, it was possible to enhance the ratio of the maximum applicable force to the structures mass for 124 % compared to a periodic structure.

Another optimization goal of the presented approach is the adaption of the struts diameters with respect to the appearing stresses. First, an optimization has been introduced, at which the struts diameters are optimized uniformly until a predetermined maximum stress is reached. Thus, it was possible to almost exactly reach the desired stress of 32 N/mm². However, the loads in the single struts were still varying.

Therefore, another second optimization approach has been applied. Here, the single struts were adapted to their respective stresses individually. However, several different procedures concerning the fixed and loose rotational degrees of freedom and the optimization goal (maximum of average von-Mises stress) had to be investigated to come to an optimization procedure, which does not lead to unwanted bending loads in the beams and which can be performed without any manual interaction. Thus, the ratio of the maximum applicable force to the structures mass could be enhanced for 80 %.

However, FEM calculations with a tree dimensional model of the structure have shown that there are severe notch stresses appearing at the nodes where the beams are merging. Therefore, a suitable node design will be developed in future works, which realizes a smooth connection of the struts and therefore reduces stress peaks.

Beyond that, another procedure for the optimization of the struts diameters will be developed, which makes it possible to reach a predefined stiffness of the structure with the application of a minimum mass.

Furthermore, a rule based algorithm will be developed, which is able to automatically build up a structure that is adapted to the flux of force of a part. Currently, this step has to be done with great manual effort.

The presented approach for the optimization of lattice structures has been applied on the example of a shear loaded beam. However, further optimizations will be done on real components from industry in the future. Thereby, the most benefit can be reached for parts which are strongly accelerated or in industries where lightweight design is of essential importance. Therefore, possible applications can be found in aviation and space flight, in automotive industries (especially electric mobility and racing) as well as in production and processing machines.

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