APPROACH FOR LOAD-ADAPTED OPTIMIZATION OF GENERATIVE MANUFACTURED LATTICE STRUCTURES

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Abstract
Due to the limited amount of resources, the consequent application of efficient lightweight design is increasingly getting important. Especially in case of mesoscopic approaches like lattice structures, SLM technologies are getting more and more applied to produce the complex parts. For calculation and dimensioning of such patterns, existing approaches mainly use the development of a homogenized, anisotropic material model in order to describe the behavior of respective structures. This procedure has limitations concerning the load-adapted optimization of the composition. For this reason, a new approach for the calculation, dimensioning and optimization of lattice structures is getting introduced. Therefore, investigations concerning an ideal course of the pattern are examined to achieve a correlation between external loads on the respective part and the ideal orientation of the struts.

Keywords:
Lightweight design, Material behavior, Dimensioning, Flux of force, Selective laser melting

1 LIGHTWEIGHT DESIGN BY GENERATIVE MANUFACTURIED LATTICE STRUCTURES

Due to the limited amount of resources and the finite fossil energy, the present ecological and economical developments are increasingly getting important for industry. The reasons for this trend are various.

On the one hand, an ecological handling of resources has a growing influence on the image of a company in public. On the other hand, the development of environmentally compatible products also brings financial advantages. This is reflected in decreased disposal costs, a higher productivity or the reduced consumption of expensive resources. Furthermore, there exist legal regulations like the European “EuP”-directive for energy efficiency and environmental compatibility. Therein, the energy consumption while the utilization phase of a product or a production facility is one main focus for the achievement of the depicted goals [1, 2].

By the consequent application of efficient lightweight design (see Figure 1), these legal regulations can be met as well as costs for the production and utilization of products or machines can be saved.

Furthermore, the reduction of masses leads to technological advances like better dynamic properties of accelerated systems [2].

1.1 Lattice structures in lightweight design

Common lightweight approaches can be differentiated in three categories depending on their geometrical dimension [2]:

- macroscopic lightweight design;
- mesoscopic lightweight design;
- microscopic lightweight design [2].

Figure 1: Application of lightweight structures in a bending loaded robot arm

Thereby, microscopic lightweight design addresses the well-directed microstructure of one and the same material, which can be reached for example by appropriate heat treatment to obtain ideal material properties.

Macroscopic approaches in contrast constitute the optimization of the part geometry in relation to the applied loads, which for example can be performed by a finite element method (FEM) based topology optimization[2].

However, mesoscopic lightweight design, as the main topic of this contribution, addresses the variation of the structure according to the applied loads on a part. This material structure can for example be arranged in terms of metallic foams, honeycombs or lattice patterns [2]. In doing so, these cellular structures modeled in terms of bionic principles show some very advantageous properties like low mass along with high stiffness and strength [3], for which reason they have a high potential for the utilization in lightweight components.

Cellular structures can be classified in periodic and stochastic types, whereat the former ones show a higher potential for lightweight applications [3]. Furthermore, periodic structures exhibit another advantage compared to periodic ones: Because of their stochastic nature, the material distribution of the latter ones is not known exactly because of the stochastic nature, why the calculation of their material behavior – and therefore the mechanical properties of parts made of them – is afflicted with uncertainties. Periodic structures, in contrast, have a regular, well known configuration, whereby the only imponderability can be due to their manufacturing process. Surveys in industry have shown that this is a very important aspect for the application of the respective approaches.

1.2 Manufacturing of lattice structures by selective laser melting (SLM)

In the recent past, the realization of lightweight strategies – especially in case of macroscopic approaches – was mainly restricted by the manufacturing technologies. Conventional processes like milling, turning or casting show a multitude of limitations concerning the geometrical freedom in part design [2]. In shape cutting for example, the accessibility to the part-surface has to be assured. In casting, basic conditions like mold removability, draft angles or wall-thickness ratios have to be taken into account.

Alternatively to those production techniques, a new category of manufacturing processes has established since the year 1986: additive layer manufacturing (ALM) [4]. In ALM-processes, the joining of individual volume elements is getting adopted to build up a part. In Selective Laser Melting (SLM) for example, the process starts up with the application of a layer of powder on a building platform. Afterwards, the powder material gets selectively solidified by melting with a laser. This is followed by lowering the platform for the thickness of one layer and the anew adoption of powder material. This procedure is repeated until the manufacturing of the part has finished [5]. Thereby, it has to be mentioned that ALM-produced components show a minor anisotropic, orientation-dependent material characteristic because of their generative composition in layers [6].

In the recent past, the application range of the SLM-process 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 of metal components [6, 7]. In case of complex parts and structures needed in small lot sizes, these techniques show advantages compared to conventional processes. Thus, it is possible to produce individual parts with tailored properties in a flexible and fast way.

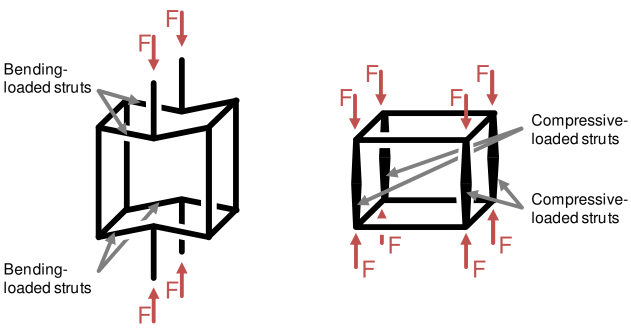
Beyond these technical aspects, economical considerations play a major role when taking the use of ALM-processes into account [7, 8]. In [8], the production costs of HSC-Milling, investment casting and ALM have been faced to each other for different sample parts, whereat the generative manufactured components have partly shown severe cost advantages especially for small lot sizes and complex structures

Therefore, for the design and production of tailored lightweight components, this kind of process features fewer restrictions concerning their part geometry as well as a reduction of costs for manufacturing and utilizing the lightweight components [2].

1.3 Dimensioning of lattice structure components

The mechanical properties of cellular materials, especially of lattice structures, can be differentiated by the main load type applied on the struts of an elementary cell. These load types can be classified in bending-dominated and stretch-dominated (see Figure 2).

In case of the bending-dominated cell types, the forces will cause a bending moment in those struts, which are oriented perpendicular to the direction of force of its adjacent struts. In the second alternative, the loads effect a compressive behavior of the struts [3].



F: Forces of adjacent struts

Figure 2: Bending-dominated (left) and stretch-dominated (right) elementary cells (according to [10])

Based on these models for elementary cells, Gibson [9] developed the most acknowledged model for strength of metallic cellular materials. His considerations are derived from assumptions of cell deformation and failure. Thereby, the corners of the cells are assumed as fixed or plastic hinges, depending on their stresses. Out of that, a first approach for calculation of the compressive strength of open-cell lattice structures was derived:

$$\frac{\sigma^*_{yield}}{\sigma_{yield,solid}} = C_5 \cdot \left(\frac{\rho^*}{\rho_{solid}}\right)^{n_5} \qquad (1)$$

Thereby, the quotient on the left side of equation (1) describes the percentage of the cellular structure's yield stress, in reference to the yield stress of the massive material of which the structure is built. Respectively, the quotient in brackets describes the ratio of the densities of the cellular structure and the massive material.

C_5 and n_5 are variables, which can be determined by experimental investigations. These examinations for compressive strength have been expanded on the identification of the behavior of e. g. tensile strength, shear strength, bending strength, Young's modulus, shear modulus, bulk modulus and Poisson's ratio [9].

It has shown that the presented approach is suitable until relative densities of 0.3, whereat the strength apparently depends mainly on the relative density of the cellular material. Thereby, stretch-dominated cellular materials show almost linear behavior with a factor n_5 of approximately 1, while bending-dominated material exhibits a factor of 1.5. Assuming that the relative yield strength for both, bending-dominated and stretch-dominated structures are equal for unity, and therefore relative densities of 1, this leads to the conclusion that stretch-dominated structures generally show higher relative strength then bending-dominated structures [3].

Furthermore, the investigations show, that elastic buckling of the struts has to be taken into account. This means that it has to be considered, if buckling strength or yield strength of the struts is lower. This concerns the failure mechanism according to the slenderness ratio of the struts and therefore the relative density of the cellular material.

In his work, Rehme [3] undertakes further investigations on the mechanical behavior of cellular structures. Thereby, he expands the presented approach of Gibson [9], which is suitable for structures with relative densities below 0.3, for high density structures above this limit. In doing so, he also takes the anisotropic material behavior of SLM-manufactured solids and lattice structures into account. The investigations made for this purpose are of theoretical and experimental nature. In case of the latter ones, he also factors the producibility of the structures by means of the SLM-technology.

For an ideal part design, the material properties should be customized for the respective task. Because the complex geometries of cellular structures do not allow a calculation of part properties without the usage of for example the Finite-Elements-Method (FEM), practical scaling laws are needed. For this reason, Rehme [3] developed dependencies for mechanical properties of lattice structures in reference to their relative density or the ratio of their cell sizes compared to the strut diameters. This can be seen in Figure 3 for the compressive yield strength of different cell types. These dependencies are based on trigonometric functions to allow the mapping of the properties for the whole range of densities, from almost zero to unity. For theoretical examinations, assumptions like described before for Figure 2 were combined with conventional beam theory [3].

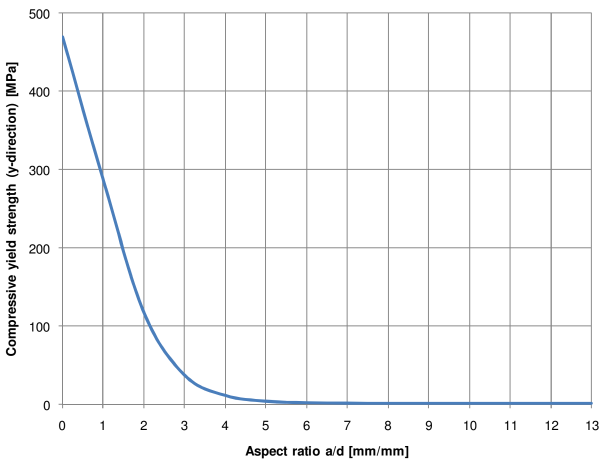


Figure 3 : Exemplary compressive yield strength types the ratio of their cell size *a* to strut diameter *d* (according to [3])

Compared to practical analyses, it has shown that the behavior of open cell structures can be predicted more accurately than for closed cell structures [3]. Furthermore, periodic structures exhibit superior strength and stiffness than stochastic structures [11].

Thus, it becomes possible to dimension components with regular structures. For this, the in fact heterogeneous material structure gets abstracted as a continuum with anisotropic material properties. This approach makes the handling of the complex material structure more comfortable for design engineers, when calculating components with these structures.

2 PRESENT DEFICITS IN DIMENSIONING AND DESIGN OF LATTICE STRUCTURE COMPONENTS

As depicted in section 1.3, in recent approaches lattice structures are getting homogenized for the calculation of mechanical properties. This way has lots of advantages when regular structures with uniform relative densities are used. The calculation and dimensioning or parts is getting comparatively easy and less time-consuming. At the same time this approach gives relatively good results.

However, the adoption of new elementary cells becomes relatively expensive since it requires a multitude of experimental investigations to determine the anisotropic mechanical properties.

Furthermore, the optimization of the cell structure in complex parts proves to be difficult as well. Here, the type and orientation as well as the relative density of elementary cells can get varied and optimized only under huge effort within a part for elaborate geometries with several different loads.

2.1 Calculation and optimization of elementary cells

To overcome the limitations mentioned above, the structure should be treated as a heterogeneous material, which is its actual state.

Of course, this means a more complex perception; but with the support of computational tools, this task can be handled without excessive effort. Thereby, the calculation of parts containing cellular structures does not require too much computing time since the structure can be processed as a framework of beams. For this purpose, beam theory, for example according to [12] or [13], can be adopted and transferred into a computer tool.

Thereby, it has to be taken into account that generative manufactured solid material shows an anisotropic behavior as described in [3] and [8]. In approaches which use analogous models with homogeneous anisotropic material behavior (see section 1.3), these aspects can be considered by an adequate design of experiments (DOE) for the determination of the properties of a structure.

By treating elementary cells of lattice structures as a formation of beams, the properties of new elementary cells as well as of cell interconnections can be calculated and determined. For this, the calculation model must meet given constraints like the density limit mentioned in section 1.3. This approach reduces the number of experimental investigations to a minimum for validation of the results or fine adjustment of the model.

2.2 Optimization of cell orientations and strut courses

According to the procedure presented in topic 1.3, the cell direction and density inside a part or at least a specific region inside a part are equal. The structure can indeed be optimized depending on the anisotropic behavior of the homogenized material model, but the cells inside the interconnection always have a regular composition.

Investigations in [2] have shown, that for non-uniform courses and values of the flux of flow inside a loaded part, this state leads to a suboptimal mechanical behavior of the respective part concerning its lightweight properties.

This can be clarified at the example of a bending loaded beam as it is shown in Figure 4. As known from engineering mechanics, the internal stress in such a beam rises linearly from the right to the left end. This disagrees with the principle of equal strain distribution in lightweight design. For this reason the density – and therefore the strength – of the lattice structure should continuously rise from the right to the left end of the beam in that way, that the stress inside the struts is kept constant along the whole beam.

Furthermore, the course of the structure should be adapted to the external constraints and loads. This correlates with the cognition in topic 1.3, that stretch-dominated cells show higher strength then bending-dominated cells. On closer inspection of Figure 4, one can imagine that inside the horizontal struts, a distinctive bending load will appear.

This state has a negative influence on the mechanical properties of the structure. For this reason, an adaption of the course of the structure would be desirable in that way, that the bending loads on the struts are getting minimized.

A similar design can also be found in many structures in nature, which have been optimized for millions of years. For example in case of the human femur, the supporting structure inside the bone, the so called cancellous bone, shows a structure which is very similar to the lattice structures treated in this contribution (see Figure 5). Especially in the area of the hip joint, the tube-shaped fibers are oriented exactly along the stress tensors, which leads to an ideal biologic lightweight design [14].

In case of the presented approach, which is based on a homogenized material model, these adoptions are hard to realize.

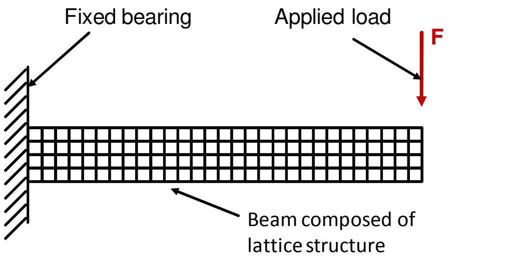


Figure 4: Bending loaded beam composed of lattice structures

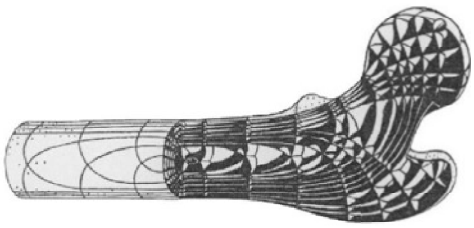


Figure 5: Course of the supporting structures inside a human femur [14]

Because of the stresses in the individual struts are not getting calculated, it is very difficult to fit the relative density of the cellular material exactly to the stresses inside a part.

In the presented approach, the orientation of the whole cellular structure can be adapted in respect to its anisotropic behavior and the external loads on a part. The course of the struts, in contrast, can not be adapted in a way, that bending loads are getting minimized.

This is on the one hand based in the fact that the basic configuration of the structure is built up extremely regular. Therefore, a variation of the course of the structure is not realizable without any modifications of the approach. On the other hand, the positions and orientations of the struts are not even deposited in the material model. This makes it additionally hard to orientate them according to the stresses inside the structure.

3 PROCEDURE FOR A LOAD-DEPENDENT OPTIMIZATION OF LATTICE STRUCTURES

As illustrated in the sections 1 and 2, recent approaches show a high potential for the calculation and dimension of components which contain regular arranged cellular structures with an uniform relative density.

It has been shown that furthermore, especially in the case of periodic structures, there is still a high potential to increase the performance in matters of lightweight design. This affects the stress tensor dependent optimization of the course of the structure. Furthermore, the relative density of the structure, and therefore the cross section area of the struts, should be adapted in reference to the particular load on the individual struts.

The following section will give a short introduction into a theoretical approach to execute a suchlike optimization.

3.1 Investigations concerning the ideal orientation of struts in lattice structures

As explained in section 2.2, the struts in an ideal lattice structure should be orientated in relation to the main stress tensors. In order to assay this thesis and to achieve clarity concerning the correlation of the strut direction and the stress tensors, a torsion-loaded hollow shaft has been examined by FEM-simulations. This example has been chosen, because it has a regular distribution of stress. This distribution on the one hand concerns the value of the stress, and on the other hand the direction of the flux of force, which has a steady orientation along a helix.

Therefore, a shaft composed of a helix shaped lattice structure has been constructed, as it can be seen in Figure 6. By means of this specimen, different parameters have been varied to determine their influence on the lightweight performance of the shaft.

One result of the analysis is that the angle of the struts has a main influence on the torsion-stiffness of the shaft. It is recognizable that the best result can be achieved with an angle of 45° for both strut directions (see Figure 6 right). This correlates with the conclusions of Mattheck [15]. According to that, shear squares are resulting from the torsion moment on the shaft (see Figure 7). Thereby, the shear forces can be added up to compressive and tensile forces at the respective corners, which both have the same value and an angle of 45° corresponding to the axis of the shaft. The struts in a lattice structure should ideally be orientated along these forces to avoid bending loads.

3.2 Procedure for gaining flux of force adapted lattice structures

As described before, for an ideal adaption of a lattice structure, the course of the struts has to be adapted as well as the relative density of the structure. To determine the latter one, the loads on the struts have to be calculated to derive suitable cross section geometries for the individual struts (see Figure 8). For the whole procedure, the process-specific constraints have to be considered.

The optimization process is based on an FEM-analysis, which calculates the flux of force within the design space for the lattice structures as well as the load transmission into the design space. These data presents the input information for a three-step optimization process.

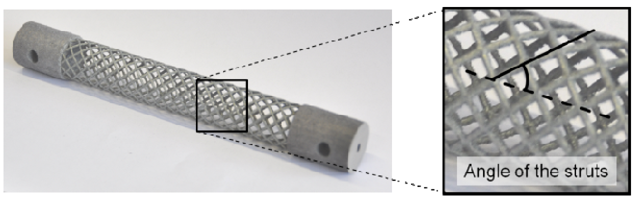


Figure 6: Torsion-loaded shaft composed of a helix-shaped lattice structure

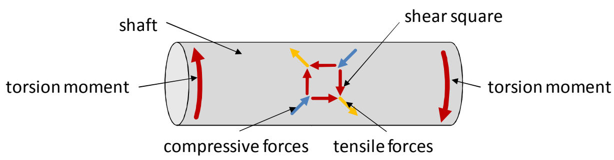


Figure 7: Shear square in a torsion loaded shaft (according to [15])

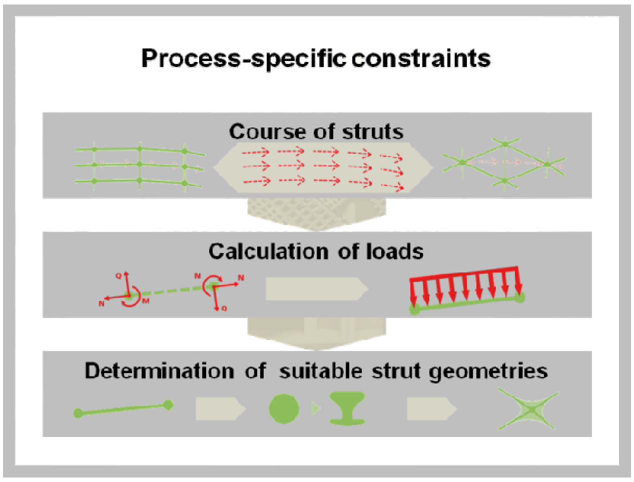


Figure 8: Procedure for flux of force dependent optimization of lattice structures

Process-specific constraints

In the context of the work, the generative manufacturing process Selective Laser Melting (SLM) is used to produce the optimized lattice structures because of its high freedom in geometrical design.

As mentioned in section 2.1, generative manufactured solids exhibit anisotropic material properties as well as some few geometrical constraints, which have to be taken into account in terms of a suitable material model.

To follow the requirements concerning the materials anisotropy, a material model which includes the respective strut orientations and geometries must be developed for the utilized process and the material. Thereby, different parameters have a differing influence on the behavior. Especially for the mechanical properties like plastic deformation or damage, this behavior can be crucial [8].

Not only the angle of the struts compared to the building platform has an influence, which is already analyzed in literature. Further impacts can appear depending on the strut length, the cross-sectional area or the cross-sectional geometry. All of these influences have to be implicated into the respective model.

Furthermore, the producibility of the struts and structures can be inspected, if the according process-related conditions are mapped.

This yields to a material model, which is adapted on the specific needs for the calculation of lattice structures and the inspection of their producibility. Based on this, the structures can be calculated and optimized using beam theory.

Thereby, the model should be arranged in such a flexible way, that it can also be used within the optimization procedure for further manufacturing processes.

Course of struts

For the development of an optimized course of struts, an FEM-analysis of the design space for the lattice structure is necessary, as mentioned before. Therefore, given part areas as well as the design space itself have to be designed. On this basis, the load transmission into the design space as well as the flux of force is getting calculated (see Figure 9).

With help of the flux of force, an ideal course of the struts gets determined.

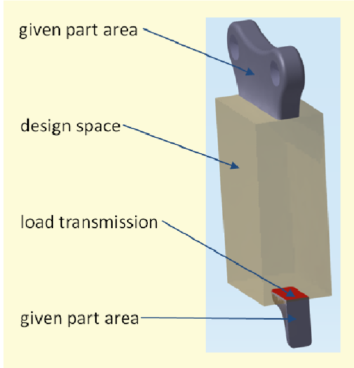


Figure 9: Pre-processing for the optimization procedure

Afterwards, an optimal orientation of the part on the building platform is calculated for this structure. Thereby, the material model, which contains the process-specific constraints, is used. Thus, the producibility of the structure is getting assured as well as best possible mechanical properties by considering the anisotropic material behavior.

Calculation of loads

With the determined course of the structure, the loads on the struts can be calculated. This step follows the classical calculation of frameworks in combination with beam theory, for example according to [12] or [13].

For this, the appearing loads on the knots in the area of the load transmission have to be determined. For this, the results of the FEM-analysis in the pre-processing are used.

Furthermore, the loads on the other knots inside the lattice structure can be computed similar to the approach of Finite-Elements calculation. For this, the stiffness matrix for the whole structure is getting derived.

All of the loads on the knots have to be determined for six degrees of freedom (DOF): three translational and three rotatory DOFs.

With the information about the loads, appearing in each knot, the applied loads on each singular struts can be derived, whereat no bending should ideally appear, even if this might not always be achievable, especially in case of combined loads.

Determination of suitable strut geometries

After the determination of the loads which appear in each strut, suitable geometries can be derived.

For this, the material model gets applied again. For each beam, the coordinates for its two knots are given to the model. With this information, the length and angle of the strut can be calculated. Out of that, the model can calculate the needed material properties like Young's modulus, yield strength, etc. for the strut. Based on these factors, the cross section area for each strut can be derived to fulfill the required properties.

Implementation into a software tool

Within the future works on the presented topic, the introduced procedure will be implemented into a software tool.

For this purpose, the FEM-calculation is getting executed via a commercial program. The following optimization will be implemented in MATLAB. Thereto, an interface between the two software applications will be defined. To make the results useable, several post-processing steps will be provided. These include an interface to a CAD-Software, the derivation of machine code for the SLM-process, as well as the visualization of the structure in MATLAB.

4 SUMMARY

A short introduction into the advantages and categories of lightweight design approaches has been given. Thereby, mesoscopic principles, especially lattice structures, are the main focus of this contribution.

Recent approaches for the calculating and dimensioning of lattice structures use homogenized material models with anisotropic behavior, to allow a more abstract view on the structures and therefore simplify their treatment. Thereby, good results have been achieved by the use of these approaches.

This procedure has limitations concerning the load-adapted optimization of lattice structures. For this reason, a new approach has been introduced, which treats the structures as frameworks. Their calculation is based on beam theory.

Therefore, it is getting possible to perform further optimization concerning the orientation and course of the struts as well as their cross section area. Hence, the structures can be optimized with regard to the flux of force inside the respective part, an approach which has proven its worth in nature for millions of years, for example in the human femur.

In further works, the presented optimization and calculation procedure will be transferred into a computer tool and validated concerning its usability and the achieved results.

5 ACKNOWLEDGMENTS

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