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Using a binary material model for stress constraints and nonlinearities up to crash in topology optimization

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Abstract
Nowadays the development of mechanical components is driven by ambitious targets. Engineers have to fulfill technical requirements under the restrictions of optimized cost and reduced weight for mechanical components simultaneously. Accordingly in the last years newly developed and tested optimization methods have been integrated in the development processes of industrial companies. Today, especially topology optimization methods have gained in importance and are often used for the design of casting parts.

Using stress or strain-energy information for sensitivities is the basic idea for all topology optimization methods. The method SIMP, today's standard in industry, uses continuous material modeling and gradient algorithms. ESO/BESO is based on discrete modeling: specific algorithms use direct, gradient or interpolated information to change the structure.

The new Topology Optimization is based on two simple, but powerful principles without any application of gradient information. This mechanism has its analogy in nature similar to the development and growth of trees and is also grounded in experiences from solving engineering problems. The lowest stressed elements are removed from the structure. At the highest stressed elements - *hotspots* in engineering terminology- material is added, which is similar to the BESO and SKO methods. Different to BESO and the SKO method, the new method uses the minimization of volumes as an objective function. A controller mechanism calculates the step sizes of added or removed material depending on the progress of the constraints in the optimization.

This approach allows an easy implementation of manufacturing restrictions and a large number of response functions. Especially manufacturing restrictions are important for industrial purposes. Due to this fact, restrictions for casting directions, minimum material strength, symmetry and forging are integrated. Developed for industrial applications, this new approach solves many academic reference problems better than other available commercial optimization tools.

In the next steps, stress constraints and optimization runs with plastic material are tested. Based on good results, all necessary response functions are used together in optimization runs during the standard industrial development process. So it is possible, to fulfill all specifications in the first concept-phase in combination with topology optimizations directly. In this way, more weight reductions, compared with results of conventional industrial topology optimization methods in use, can be achieved.

The current field of research work is to investigate topology optimization with a crash load case. In this topology optimization an explicit FEA analysis is integrated.

Keywords: topology optimization, binary material method, stress constraints, nonlinear FEA analysis, crash load case

1. Introduction

Today several approaches are in use for topology optimizations. The starting point for FEA based topology optimization can be found in literature in [1]. Bendsøe introduced his homogenization method first [2]. Parallel to the homogenization method, Bendsøe presented the SIMP approach (Solid Isotropic Microstructure with Penalization) [3]. This method gained popularity because other researchers applied it to their work [4]. Today the SIMP approach is a standard method for topology optimizations. For example, the commercial tool Tosca® from FE-Design [5] is based on SIMP. SIMP uses the element densities as continuous design variables. The coupled stiffness values of the elements transfer the modifications of the optimization to the structure results. At the end of each topology optimization run, a discrete distribution for the interpretation of the results is needed. For this reason, the SIMP approach penalizes intermediate density values using a penalization factor to assign lower stiffness values to these elements [13]. SIMP is combined with gradient algorithms, e.g. the method of moving asymptotes [7].

Since 1992 two other important approaches have been developed and published: ESO/BESO and the SKO method. The Evolutionary Structural Optimization (ESO) is focused to remove unnecessary material from too conservatively designed parts [8]. For ESO, it is only possible to remove material. A binary element modeling is in use in comparison to SIMP [9]. To enable material growth, Querin introduced the Additive Evolutionary Structural Optimization method (AESO) [10]. AESO adds material to areas in order to improve the structure. The combination of ESO and AESO leads to the Bidirectional Evolutionary Structural Optimization [BESO] method [8, 9, 12]. The main idea behind ESO, AESO and BESO is to remove lowly stressed elements and adding material to higher stressed regions. To designate these elements, a so called "reference level" is defined. Elements below the reference level are removed from the structure. In the surrounding of elements with higher stresses then the reference level, material is added. During the optimization this level is adapted to the optimization progress. BESO uses here - depending on the individual approaches - direct, gradient or interpolated information about material properties to change the structure [9]. Due to these facts, for ESO/BESO the compliance-volume product can be assumed as an objective function [6].
The Soft Kill Option method (SKO method) was introduced by Mattheck, Baumgartner and Hartzheim in [13]. Inspired by the growth of trees and bones, the biological growth rule was formulated. In highly stressed areas material can be added and in lowly stressed areas material will be removed. Homogeneous and constant stresses should be generated especially at the surface of the structure. To change the structure, the SKO method modifies the Young Modulus of the FEA-elements as a function of the temperature. High temperature indicates high Young Modulus and low temperature causes low Young Modulus [11, 13, 14, 15].
The SIMP method in combination with gradient algorithms achieved a widely-used application in industry. Main reason for the success of the approach is the integration of manufacturing restrictions [16, 17, 18]. Without manufacturing restrictions, it is impossible in most cases to get a feasible design for real life problems. Today nearly no suggestions for the integration of manufacturing restriction for BESO and the SKO method have been published. Only for SKO a further development, called Topshape®, which offers manufacturing restrictions, has been published [19].

2. The new approach for topology optimization

The new approach for topology optimization is designed for industrial purposes. Taking into consideration, for engineering and daily work, the optimization focus is on the improvements of existing results instead of searching for global optima. Main targets are costs and weights of the parts. In the development of casting parts, a reduction of weight is coupled with a reduction of material costs. So it is consequent to use the weight as target function. Additional important aspects are the necessary time and costs in the development process. To achieve this and to improve the general usage, linear and nonlinear FEA analysis should be combined with the new topology optimization method. Nonlinear effects can be found for example in plastic material behavior as well as by bushings and by contact problems. Finally the last point, manufacturing requirements need to be fulfilled [20, 21].

2.1. Main process of the new topology optimization method

The flow chart in figure 1 illustrates the main steps of this new topology optimization method. A step size controller calculates first a basic rate. Depending on this basic rate, the numbers of removing and adding elements are defined for the modification of structural elements. According to the added element, hotspot areas are corrected. After this correction process, the lowest stress elements depending on the reduction rate are removed. After adding and removing elements, the structure will be checked to insure it is connected: all force transmission points must be connected to the support elements. If this check fails, the controller modifies the correction and reduction rate in order to produce a feasible structure. During the heuristic steps, non-connecting elements are removed from the structure.
The interface routines for the FEA solver are integrated in the optimization software. After finishing all changes and checks, the optimizer writes the solver specific input decks with all active elements and coupled nodes. After the FEA analysis, the post-processing evaluates all target functions and constraints. An interface transfers this information to the controller.

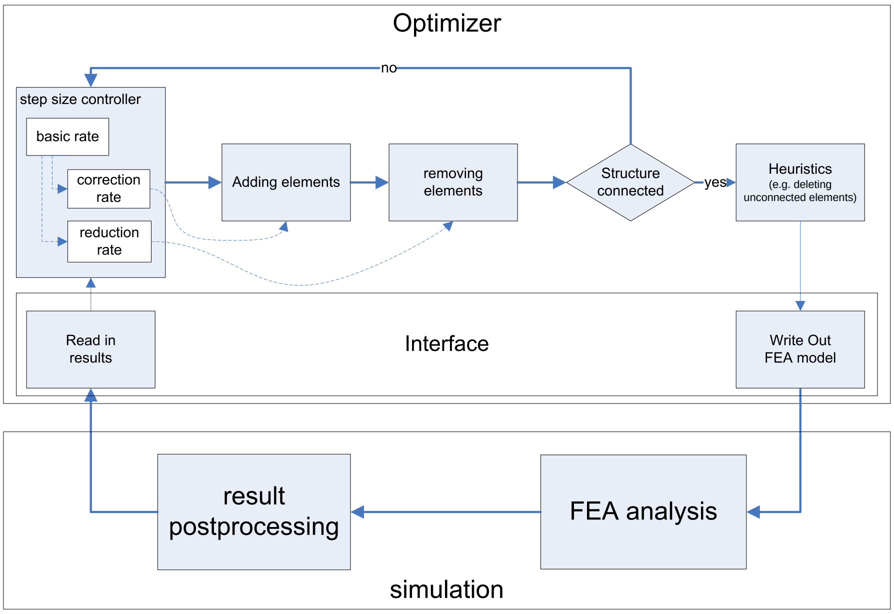

Figure 1: Flow chart of New Topology Optimization Method

2.2. Step size controller

The step size controller is an important element of this new method. The main idea is to control the target function "weight" by using the progress of the constraints during the optimization. In the first step, the basic rate is modified. In a second step the reduction and correction rate are calculated depending on the basic rate to vary the structure.

The basic principle is simple. A smooth increase or decrease of the constraint function allows the removal of more elements up to the allowed maximum. In the other case, when the constraint increases, the step size is reduced, allowing only a limited number of elements to be removed but more hotspots have to be fixed. When a structure violates the maximum allowed constraint limit two times one after another interaction, the step size has to be reduced significantly: no elements are removed. In such a situation it is only allowed to add new elements to the structure. This is based on a simple heuristic from engineer's knowledge.

Figure 2 describes the change of the basic rates dependent on the possible events and the coupling between basic rate, correction and reduction rate. High basic rates allow high reductions and less corrections will be necessary. For basic rates from 0.1 to 0, fewer reductions should be carried out. When the basic rate tends to zero, more corrections are needed. Only corrections will be done in case of a basic rate lower than zero [20].

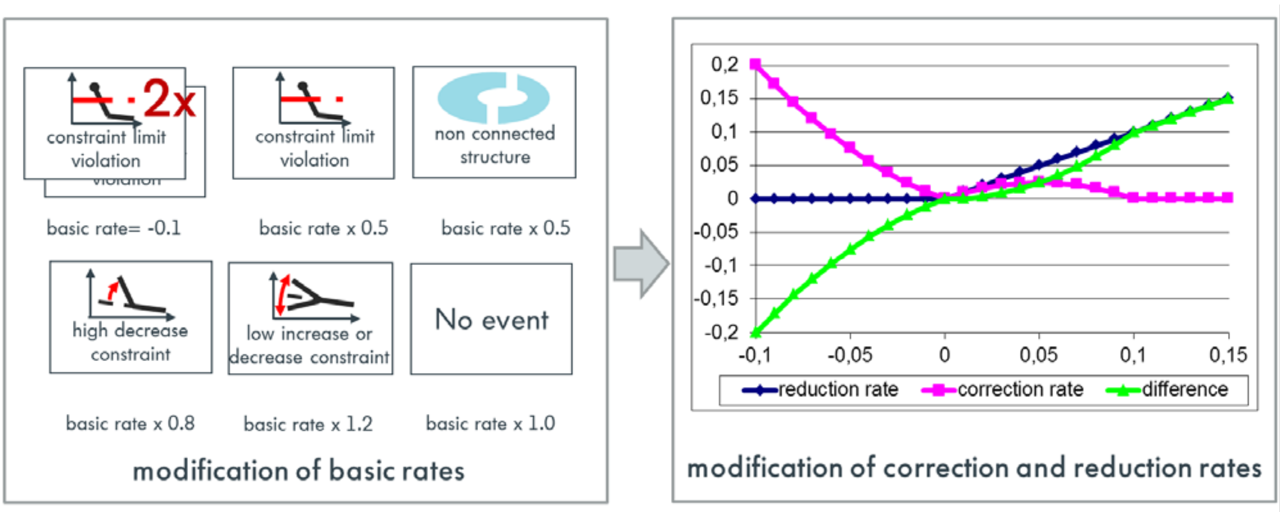

Figure 2: Step size controller modifications on the basic rates cause variations on correction and reduction rates

2.3. Adding and removing material in the structure

After the calculation of the step sizes for corrections and reductions, the structure will be modified. To avoid problems in the FEA-simulation only binary states of the material are allowed: material is solid or not available. This binary material modeling allows only a switch between both states. Similar to ESO/BESO and the biological growth rule, material will be added at the highest stress values and removed at the lowest stressed regions. In figure 3 the process is illustrated. Instead of any calculated derivations of properties to generate gradients, the stress values of the structure will be sorted in descending order. Using the step size for corrections, the neighbor elements next to the highest stress values will be added to the structure and the elements with the lowest stress values according to the reduction rate will be directly removed from the structure.

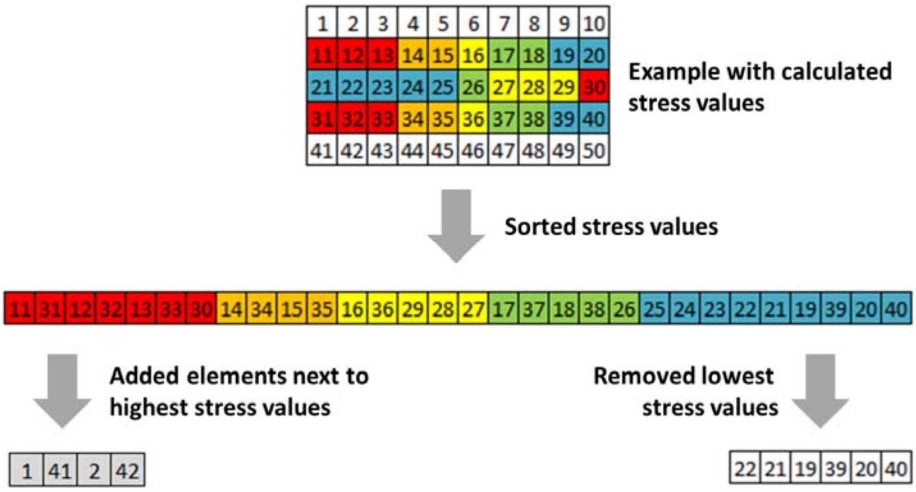

Figure 3: Modifications of an example structure by adding and removing elements depending on calculated stress values

2.4 Smoothing stress values

The stress values of elements in the structure causes the main influence on the optimization process. To avoid unrealistic high stress levels from singularities in the mesh and thin structures, a modified stress filter is used. This stress filter is based on the Sigmund Filter with small adaptions [27].
In the equation 2.01 and 2.02 the filter function is formulated with the modified and unmodified stress values $\widetilde{\sigma_e}$ and σ_i, the design variables x_e and x_i, the $\widehat{\mathrm{H}_\mathrm{i}}$ as weighting factor, the filter radius $\mathrm{r}_{\min}$ and the indices for the elements *i* and *e* as:

$$\widetilde{\sigma_e} = \frac{1}{\sum_{i=1}^{N} \widehat{H_i} \cdot x_e} \cdot \sum_{i=1}^{N} \widehat{H_i} \cdot x_i \cdot \sigma_i \qquad (2.01)$$

with

$$\widehat{\mathrm{H}_\mathrm{i}} = \mathrm{r}_{\min} - \mathrm{dist}(\mathrm{e}, \mathrm{i}), \qquad \{\mathrm{i} \in \mathrm{N} \mid \mathrm{dist}(\mathrm{e}, \mathrm{i}) \leq \mathrm{r}_{\min}\} \qquad (2.02)$$

According to the binary structure model, the design variables have only the two states “0“ or “1“. The filter radius is active in a range between 1 and 2 [28]. In the figure 4 the space relationship between the design element in the middle and the other elements around it, is illustrated. The distance of two elements is measured between their center points. From a distance between 1 and $\sqrt{2}$ only the direct neighbor elements are involved. The number of considered elements rises with a distance larger than $\sqrt{2}$. All elements are included with a radius beginning $\sqrt{3}$ in a three dimensional structure. By increasing the filter radius, the stress values of the design elements will be smoothed more.

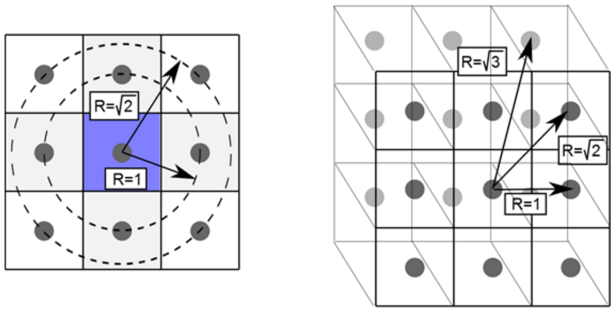

Figure 4: Space relationship of elements for the function of the stress filter

2.5 Integration and implementation of the FEA simulation

The integration and implementation of the FEA simulation can be done very easily. No special material model without mayor modifications and programming work must be integrated into the code. The input deck for the FEA simulation is identical to an input deck for single simulation of a design. The interface of the optimizer writes a standard input deck of all existing elements. No removed elements will be written out. Due to this fact all FEA solvers can be used. For the simulation of the examples in this paper, Abaqus® has been used [22]. Linear, nonlinear and explicit simulations can be performed with Abaqus® [23, 24] based on the theory of the FEA [25, 26]. Using the integrated scripting procedures the stress values and constraints will be extracted to files. The optimizer starts the next optimization loop based on the information from these files.

3. Examples

To illustrate the work of this new topology optimization method, two examples are given. In the first example an academic control arm combines a normal use load case and a misuse load case with constraints for stress and reaction forces. In the second example an optimization of a crash scenario is shown.

3.1 Academic control arm

In this example a three-point control arm is used for the optimization. This academic example is derived from a realistic car part. The design space is simplified and the used forces are modified. The control arm is fixed in all degrees of freedom at the two kinematic points at the top of the structure in figure 5. At the third point the degree of freedom in Z-direction is fixed. The direction of the forces for normal use and misuse are shown in figure 5. For the normal use load case aluminum with a linear material model and for the misuse load case a nonlinear material model (yield point at 200MPa, tensile strength at 300MPa and failure strain at 10%) is used for the simulation. The FEA mesh contains 43830 brick elements with an edge length of 5mm.

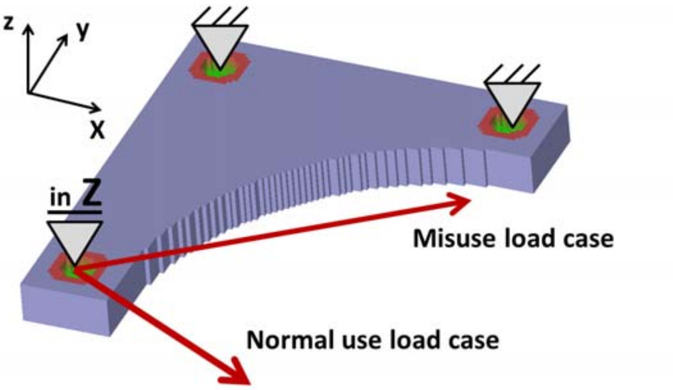

Figure 5: Design space and load cases of an academic control arm

In the first iterations, demonstrated in figure 6, the optimizer removes the majority of material between the two supporting structures at the top of the control arm. In iteration 8, a second hole is inserted in the middle of the structure. This hole increases over the next iterations. Between iteration 15 and 20 two smaller holes with the shape of small triangles are inserted at the point of force transmission and in the middle of the structure. From iteration 25 to the end, the optimizer defines the final shape of the design and no topology changes happen anymore.

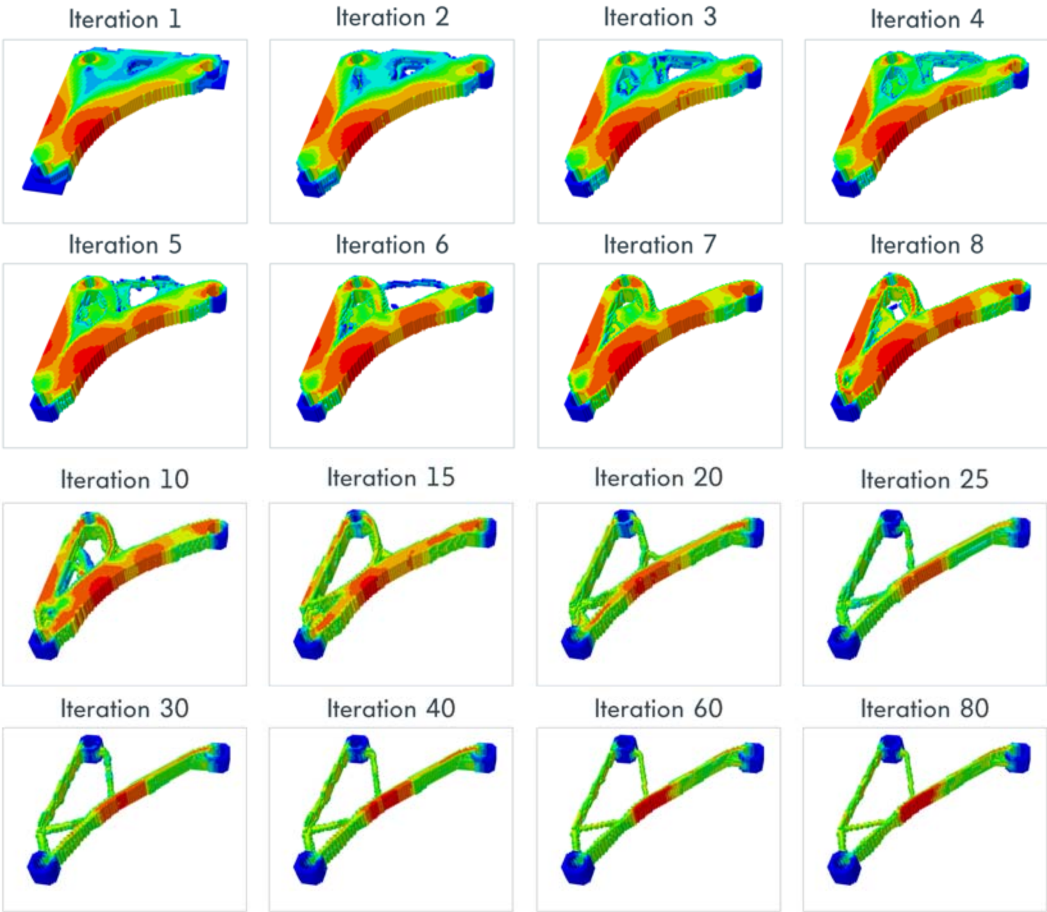

Figure 6: Design changes during the optimization process of the academic control arm

The optimization process starts with 43830 elements, which is shown in figure 7 with the blue line. During the first iterations a strong reduction of elements is reached, down to 7696 elements in iteration 26. In iteration 27 and 28, the constraints violate a limit. For this reason, material is added in iteration 29. From this iteration to iteration 59, the reduction of material is possible and no constraint violations appear. After iteration 60 the constraints oscillate around the limit. In this phase, small reductions of weight are possible. At the final result in iteration 80, only 5770 elements are part of the structure.

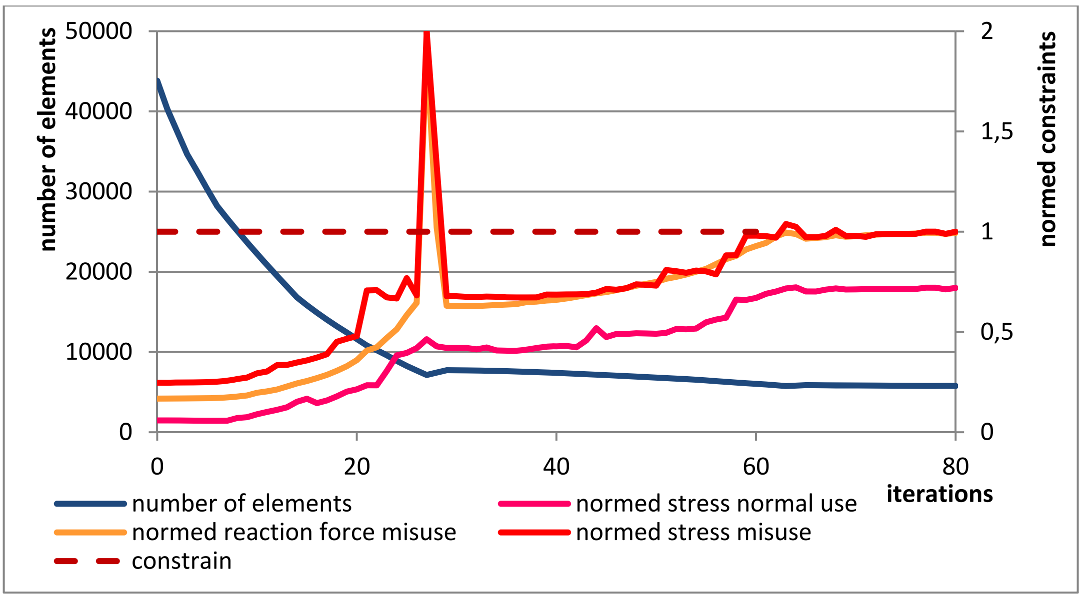

Figure 7: Target function and constraints during the optimization process of the academic control arm

In figure 8 the stress and plastic strain values of the final design are plotted with a deformation scale factor of 2. The normal use load case is less important. The structure is dimensioned by the misuse load case. The stress plot of the misuse load case shows the balanced distribution of material and a good usage of the available material. The plastic strain plot shows, that plastifications exist in large areas. Interesting details are the two smaller bars in the structure. Due to the binary material model, it is possible to simulate these nonlinear plastic and geometrical effects.

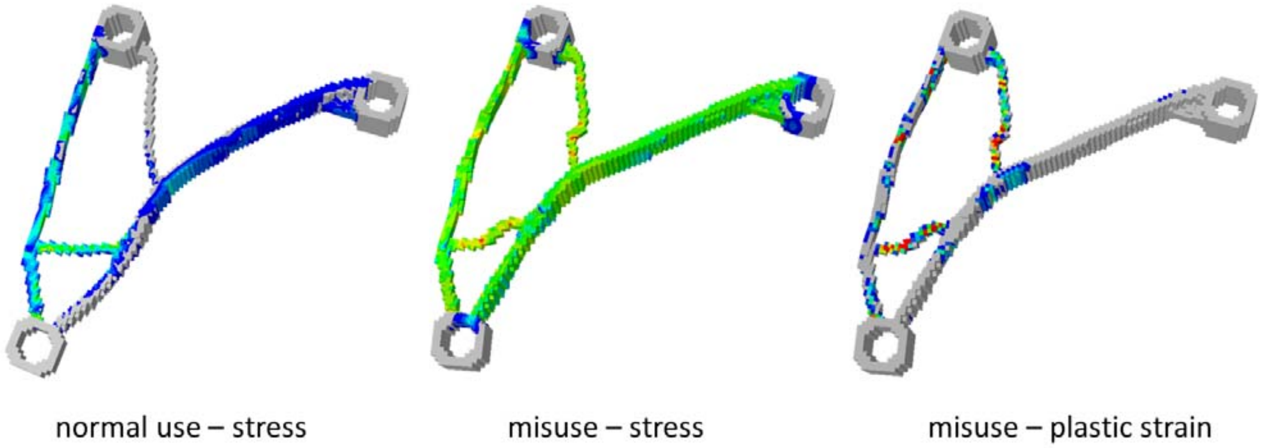

Figure 8: Result plots of the final design of the optimization process of the academic control arm

3.2 Crash Example

This example is based on a crash example from [29]. To use the example in combination with the new topology optimization method, a couple of modifications have to be introduced. In this simple example shown in figure 9, a shell mesh is used. On the left side the structure is fixed in all degrees of freedom. The blue area is design space and the red colored parts are non-design. The mesh consists of 9600 quad elements with an edge length of 1.25mm. A solid cube with an initial speed of 20m/s will be moved against the structure. The used material model for the plastification is illustrated in the figure 9 as flow curve. It starts with 1MPa and increases linearly. In the optimization an explicit simulation is integrated for analyzing the structural behavior. Two constraints, a maximum stress level (10MPa) and a maximum displacement of nodes in the structure (5mm), are activated during the optimization process.

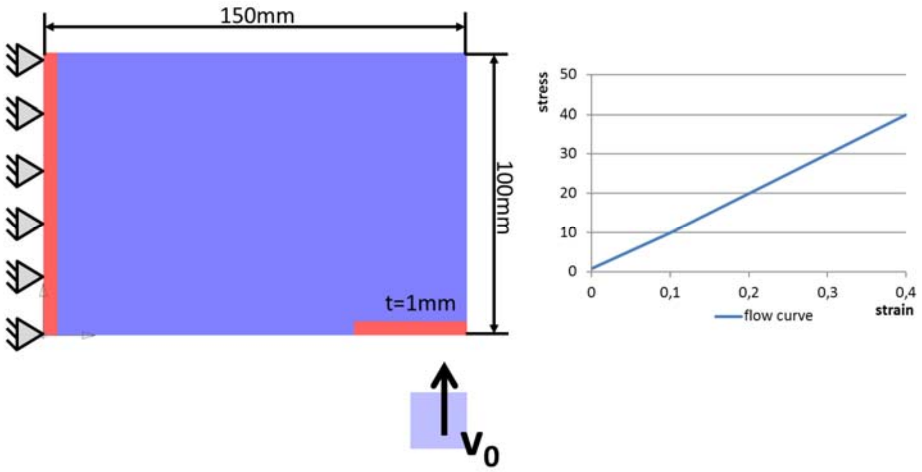

Figure 9: Design Space and flow curve of the simple academic crash example

The optimization process starts the first iterations with an irregular stress distribution based on the explicit simulation, which is illustrated in figure 10. The optimization process needs five iterations to design a valid structure. Between the two strong arms at the top and the bottom of the structure a framework is formed. In the iterations from 5 to 15 the framework is reduced to one beam. The top arm is divided in two smaller arms at the impact point and a small hole is inserted in the bottom arm. Beginning with iteration 15 the optimizer defines the final shape of the structure.

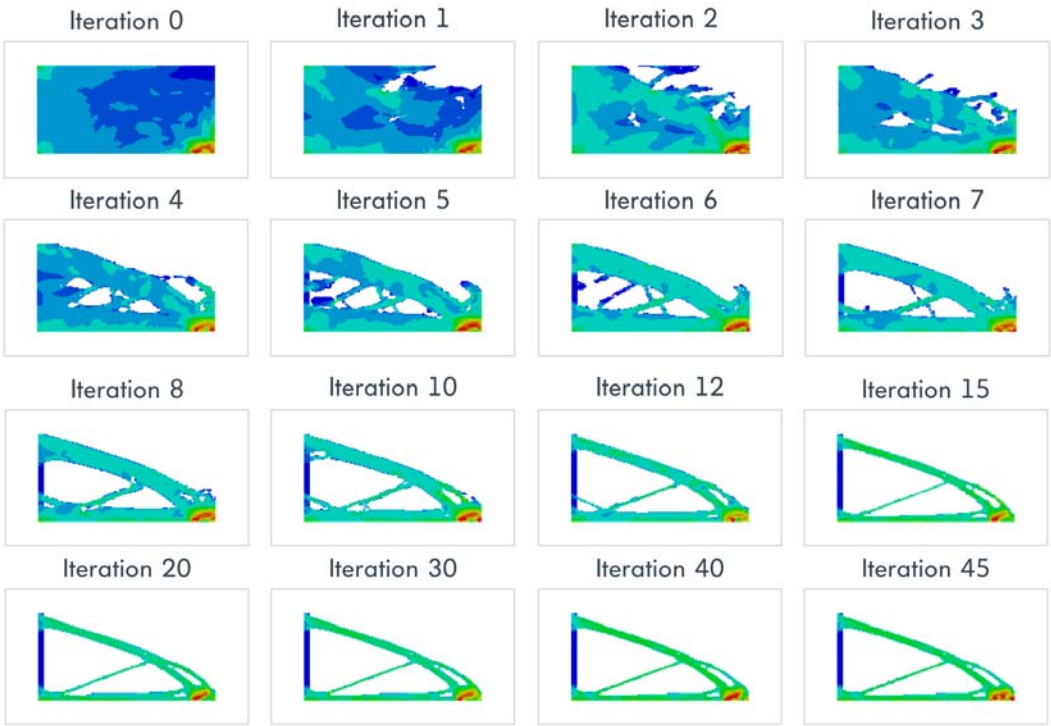

Figure 10: Design changes during the optimization process of the academic crash example

In Figure 11 the target function and the two constraints for a maximum stress in the design area and the maximum displacement over the iteration steps are shown. From the first iteration to iteration 14 a strong reduction of the target function is reached. At iteration 14, 2426 elements are part of the structure. In iteration 15 and 16 two violations of the displacement constraint forces an addition of material without any material reductions. Up to the iteration 33 the optimization reduces the number of elements to 2278. In the next two iterations, once again material must be added to the structure because the constraint is violated twice. In the last iterations the final number of 2270 elements is reached. Over the complete optimization the stress constraint doesn't reach the limit.

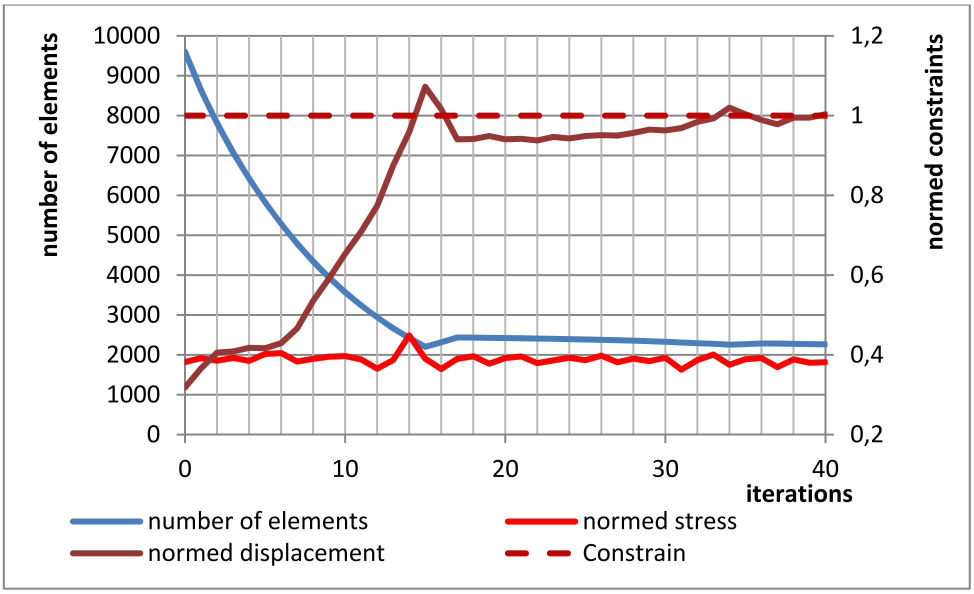

Figure 11: Iterated results of the target function and the constraints during the optimization process of the academic crash example

In figure 12, the explicit crash simulations of the final design are illustrated. The highest stress values are reached in the moment, in which the solid cube hits the structure. From this momentum the structure starts the plastification process. Over the time period of the simulation, the complete structure shows plastifications and due to this a good usage of material. At the end of the simulation the cube loses contact to the main structure.

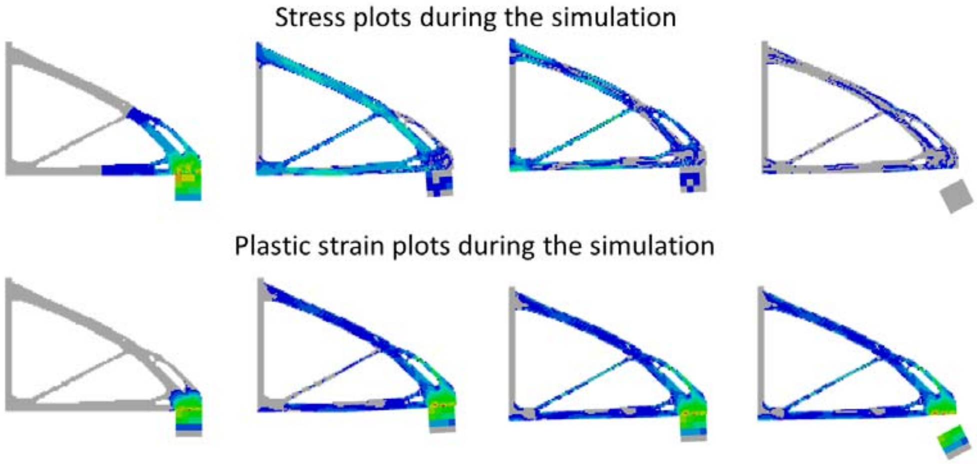

Figure 12: Crash simulation of the final design of the simple academic crash example

4. Conclusion

In this paper the progress in the development of a new topology optimization method for industrial applications is illustrated. Especially stress constraints and nonlinear simulations with plastic material behavior are efficient for the development of new parts. After the integration of the new topology optimization method into the standard development process for chassis components, possibilities of new fields of applications have been investigated and first results are shown here. Especially in the second example in chapter 3 an explicit simulation for crash analysis is demonstrated.

In general the given two examples show the wide field of applications of the newly developed optimization method. Because of the minimization of weight as target function in combination with all industrial necessary constraints it is possible to fulfill directly all specifications for casting parts after the topology optimization. This saves manual development loops compared with commercially available topology optimization tools. Additionally, the final structures have less weight as results of the optimizations. By saving weight and material costs, fuel consumption and CO_2-emissions can be reduced. In this way the development of mechanical components can fulfill the ambitious targets of the automotive industry.

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