Struct Multidisc Optim (2005) 30: 491–497
DOI 10.1007/s00158-005-0553-x

INDUSTRIAL APPLICATIONS

Lothar Harzheim · **Gerhard Graf**

A review of optimization of cast parts using topology optimization

I - Topology optimization without manufacturing constraints

Published online: 28 October 2005

Abstract In recent years, there has been considerable progress in the optimization of cast parts with respect to strength, stiffness, and frequency. Here, topology optimization has been the most important tool in finding the optimal features of a cast part, such as optimal cross-section or number and arrangement of ribs. An optimization process with integrated topology optimization has been used very successfully at Adam Opel AG in recent years, and many components have been optimized. This two-paper review gives an overview of the application and experience in this area. This is the first part of a two-paper review of optimization of cast parts. Here, we want to focus on the application of the original topology optimization codes, which do not take manufacturing constraints for cast parts into account. Additionally, the role of shape optimization as a fine-tuning tool will be briefly analyzed and discussed.

Keywords Shape optimization · Topology optimization · Optimization of cast parts · Optimal rib arrangement · CAO · SKO

1 Introduction

The optimization of cast parts is one of the major challenges in engineering because, although the designer has considerable freedom to design a component, the likelihood of generating a nonoptimal design is very high. Here, topology optimization has been established as an important tool for optimizing engineering components, for which linear analysis is sufficient to describe the performance of the component and where optimal strength, frequency, or stiffness are the objectives. This is the case for most cast parts in the chassis area and for parts such as engine brackets. Here, topology optimization helps in finding the optimal features of a component, such as the optimal cross-section or, for ribs, the optimal number and arrangement. Only if the design of a cast part has these optimal features, the whole potential for optimization is available. It has been found that the determination of these features gives the largest amount of the optimization potential, whereas the fine-tuning using sizing or shape optimization typically gives only a minor contribution (Harzheim and Graf 1995, 1996; Harzheim et al. 1999).

We will restrict ourselves to problems where strength or maximum stiffness is desired. Usually, strength is the problem in practice, but there are indications that the results for both objectives are the same or at least close together (Pederson (1998, 2000)). Hence, it is promising to use a tool for maximum stiffness even if strength is the objective.

Topology optimization uses the homogenization or Simple Isotropic Material with Penalization (SIMP) approach (Bendsoe and Kikuchi 1988; Bendsoe 1989, 1995; Fuchs et al. 1999; Harzheim and Graf 1995, 1996; Harzheim et al. 1999; Hassani and Hinton 1998; Mlejnek and Schirrmacher 1993; Olhoff et al. 1998; Rozvany et al. 1995; Yang 1997; Young et al. 1999; Zhou and Rozvany 1991). Here, the structure is described in terms of elements with high density or stiffness, whereas elements with low stiffness values (void elements) correspond to the void area. This results in a very flexible optimization method where very simple initial designs can evolve into very complicated and complex structures. Such flexibility is needed for the determination of the optimal global features of cast parts. However, the price for this flexibility is that rough design proposals are created which cannot be used directly but have to be interpreted. The challenge is to create a feasible design as close as possible to the proposal. The closer we come to the proposal, the better the result will be.

Topology optimization has been applied very successfully at Adam Opel AG for cast parts for more than 10 years (Harzheim and Graf 1996; Harzheim et al. 1999). In most cases, the in-house code Soft Kill Option (SKO) (Harzheim and Graf 1995) has been used. It is an empirical method, which was developed in the Research Center in Karlsruhe (Baumgartner et al. 1990; Mattheck 1990). It is based on the simulation of the adaptive biological growth rule of biological growth carriers like trees and bones. Experience has

Lothar Harzheim (✉) · Gerhard Graf
International Technical Development Center,
Adam Opel AG, IPC S1-01, VD&S, 65423,
Rüsselsheim, Germany
e-mail: Lothar.Harzheim@de.opel.com
e-mail: Gerhard.Graf@de.opel.com

shown that the growth rule leads to designs with uniform surface stress. Consequently, SKO is the appropriate tool for strength problems, which appear most often in cast parts.

In contrast to SKO, the approach of OptiStruct (Bendsoe 1995; Ma et al. 1992; Altair Engineering, Inc. 2002) is more flexible, because nearly every response, such as compliance, frequency, or displacements, can be used as objective function or constraint. Consequently, OptiStruct is the perfect supplement to SKO and has been used at Opel for stiffness or frequency problems.

It is not our intention to focus on the application of the SKO method, even though most of the examples in this paper have been done with SKO. The main reason for this is, apart from the argument that SKO seems to be appropriate for strength problems, that we can include modifications and adaptations in the in-house code very quickly for nonstandard problems. However, the general message and the procedures in this paper are independent from the code, and all examples could be solved with another code as well. Nevertheless, we want first to introduce the CAO and SKO methods in "Computer Aided Optimization and Soft Kill Option", because they are not very well-known, and the background is needed for the TopShape algorithm, which was the first code that was able to take manufacturing constraints into account and which will be described in the second part of this review paper. In "Practice and applications", we show applications and describe an auxiliary model to obtain the optimal rib arrangement. Afterwards, we discuss briefly the problems of the fine-tuning using shape optimization.

2 Computer aided optimization and soft kill option

The Computer Aided Optimization (CAO) and the Soft Kill Option (SKO) methods are empirical methods, which were developed in the Research Center in Karlsruhe (Baumgartner et al. 1990; Mattheck 1990). Both are based on the simulation of the adaptive biological growth rule of biological growth carriers such as trees and bones, which can be described simply as:

- Add material at high stress areas.
- Remove material at low stress areas.

The second rule is fulfilled for bones but not for trees and can be used as an option. Experience shows that the growth rule leads to a design with uniform surface stress. Consequently, it can be used for strength problems. Even if there is no definitive proof, we can expect to obtain also weight-optimized components because, obviously, the growth rule has been proven as the best in nature, a hard competition environment, in which there is no room for a waste of material.

CAO is a shape optimization code where the shape is described by the FEM mesh, and the shape modifications are obtained by the moving of grid points. The surface area where the shape should be modified is defined by a set of surface grid points (growth nodes) in the FE model. In every iteration, the location of every growth node k will be modified by adding the growth displacement $\mathbf{d}_k$ to the coordinates, with the calculation as follows (Harzheim and Graf 1995, 1996):

$$\mathbf{d}_k = s(\sigma_k - \sigma_{\mathrm{ref}})\mathbf{n}_k \tag{1}$$

Here, σ_k is the grid point stress of node k, $\mathbf{n}_k$ the normal vector at the location of node k orientated to the outside, s a scale factor and σ_{ref} the reference stress. The latter defines the low and high stress area. If σ_k is higher than σ_{ref} , we have a high stress area, otherwise the area is low stress. Obviously, this formula simulates the desired growth behavior. As mentioned above, the algorithm results in a design, in which all growth nodes have the stress level σ_{ref}.

For stress, we usually choose the von Mises stress, but one may also take other stresses. For a multiple load case, which is usually needed in practice, we use for σ_k the maximum stress value in all load cases of each grid.

SKO is a code for topology optimization. Here, the growth rule is not only applied to the surface area, but also to the inside of a component. Only isotropic materials are used in SKO and for every single element, the Young's modulus E is modified in the interval $E \in [E_{\min}, E_{\max}]$. Here, $E_{\max}$ is the Young's modulus of the used material and simulates the solid area, whereas $E_{\min}$ is a very small value, which approximates the voids in the structure. A value of $E_{\min} = E_{\max}/1,000$ has been proven empirically to ensure numerical stability. A simple way to control the Young's modulus of every individual element is provided by the option in the common FEM codes, defining the material properties of an element as a function of the grid point temperatures. We relate $E_{\max}$ to a temperature above 100, $E_{\min}$ to a temperature below 0 and define a linear relation in between (Harzheim and Graf (1995)). Starting the optimization procedure with a temperature value of $T_k^{(0)} = 100$ for all nodes, we compute in iteration i the new temperature $T_k^{(i)}$ of grid point k using the formula (Harzheim and Graf 1995, 1996; Harzheim et al. 1999):

$$T_k^{(i)} = \tilde{T}_k^{(i-1)} + s(\sigma_k - \sigma_{\mathrm{ref}})$$

$$\tilde{T}_k^{(i-1)} = \begin{cases} 100 & \text{if } T_k^{(i-1)} > 100 \\ 0 & \text{if } T_k^{(i-1)} < 0 \\ T_k^{(i-1)} & \text{otherwise} \end{cases} \tag{2}$$

These temperatures have no physical meaning, but they allow an easy variation of the Young's modulus and the visualization of the proposals as a temperature iso-surface for $T = 50$.

Usually, it is much easier for the user to prescribe the desired volume fraction of the design space than to select a reasonable value for the reference stress. Hence, the prescribed volume fraction option has been implemented in SKO, where the code computes the reference stress needed to fulfill the volume fraction constraint (Harzheim and Graf 1996).

In contrast to other methods, the SKO method is driven by the stresses in the proposal. This leads to a significant dependency of the results on the element size. The smaller the element size, the clearer are the details, which can be resolved. This leads to the effect that structure shrinks away and vanishes from the proposal, if it becomes smaller than the mesh size. This again changes the stress distribution of the current structure and, driven by the growth rule, leads to the evolution of a design, which is the optimum design without details smaller than the element size. We can consider this effect as a kind of constraint, which enables the user to allow only details in the magnitude of interest. Such kind of control has also been added as minimum member size control in the code OptiStruct (Altair Engineering, Inc. 1999).

There are some methods which are very similar to SKO, such as the hard kill method (Hinton and Sienz 1993), where a step function is used instead of the linear relationship for the Young's modulus as described above. Another similar method is Evolutionary Structural Optimization (ESO). The main difference to SKO is that the original ESO (Xsi and Steven 1993) can only handle 2D structures for a single load case, and that the low stresses material is removed, but no adding of material in high stressed areas is possible. The further development of ESO is B-directional Evolutionary Structural Optimization (BESO), which works also for 3D structures and multiple load cases and where also the adding of material is included (Young et al. 1999).

3 Practice and applications

3.1 Optimizing of a radiator support

The example of a radiator support in Fig. 1 shows the potential of topology optimization. The goal was to improve

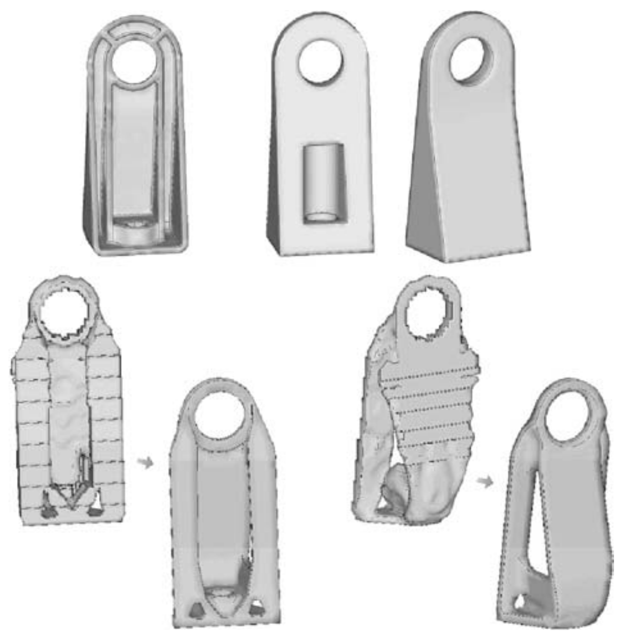

Fig. 1 Optimization of a radiator support. *Upper row*: Initial design (*left*) and two views of the available package space. *Lower row*: Two views, each showing the smoothed design proposal after topology optimization using SKO and the resulting final design

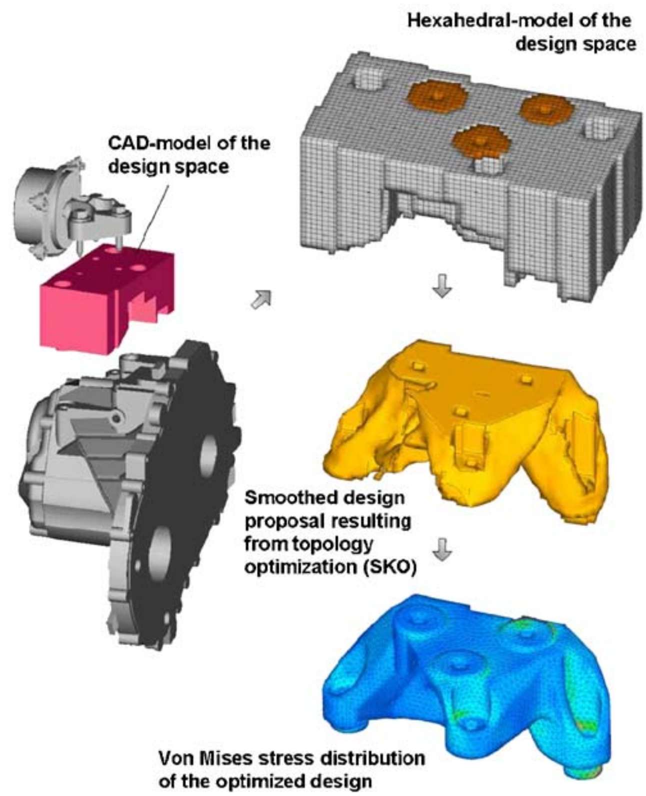

Fig. 2 Improved design process where, in the first step, topology optimization is applied to find the optimal features of the cast part, which are then included in the first detailed model of the component

the strength and stiffness without increasing the weight. It is very impressive to see that not only have the stress and compliance level been reduced by 64 and 52%, respectively, but the weight has been reduced by 31% as well.

3.2 Improved design process

The example of the radiator support is a good demonstration of the potential of topology optimization, but it is not a good approach for practical application. It is not efficient that the designer creates a detailed model of a component, which will be thrown away after computation and application of topology optimization. An improved design process is shown in Fig. 2. Here, the first step is only to define the available package space, the so-called design space. We apply topology optimization to compute a proposal within this design space, which will be used to determine the optimal features. Based on this, the first detailed model of the component will be created, containing these optimal features. In the final steps, fine-tuning can be applied to reach the real optimum.

3.3 Optimization of an engine bracket using the improved design process

The engine bracket in Fig. 3 is an example of an optimization using the improved process. Obviously, no evaluation of the

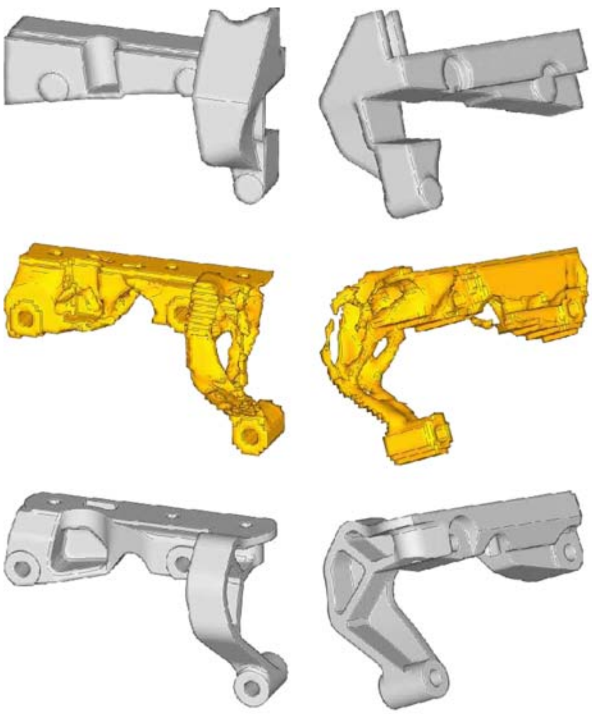

Fig. 3 Optimization of an engine bracket using the improved design process in Fig. 2. Two views, each showing the design space (*top*), the smoothed proposal (*middle*), and the resulting final design (*bottom*)

improvement in comparison to an initial design can be given anymore because the latter does not exist.

3.4 Problems in practice

In recent years, the improved optimization process with integrated topology optimization has been used very successfully at Adam Opel AG, and many components have been optimized (Harzheim and Graf 1995, 1996; Harzheim et al. 1999). Nevertheless, there are some remaining problems, which make the application difficult.

1. The interpretation of the proposals is sometimes very difficult. Whereas often it is not such a big problem to recognize an optimal cross-section, it is usually difficult to identify the number and the arrangement of ribs.
2. The fine-tuning process is time-consuming and has mostly to be done by hand. The reason is that for strength problems, shape optimization is usually needed for fine-tuning. The definition of the shape variations for the optimization code is very difficult, time-consuming, or even impossible in an acceptable time frame.

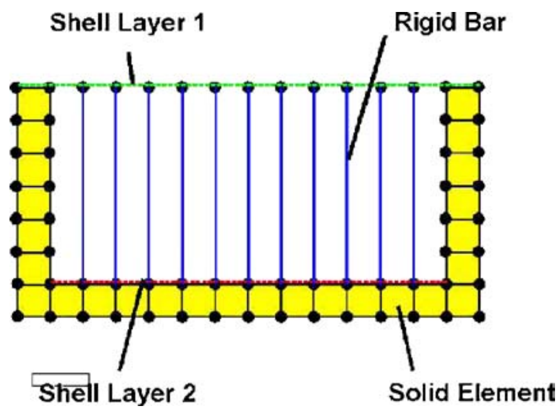

Fig. 5 Schematic sketch of the auxiliary model for optimizing the arrangement of ribs

None of the problems have been completely solved, but at least the situation has been improved for some applications. This is the case for the problem of determining ribs inside an open cross-section using topology optimization. As described in the next section, an auxiliary model can be used to improve the situation. Afterwards, we will discuss the problem of fine-tuning using shape optimization.

3.5 Determination of ribs using an auxiliary model

One problem, which occurs very often in practice, is the determination of ribs within a cast part. As a typical example, Fig. 4 shows the design space of an engine bracket and the proposal obtained with the topology optimization program SKO. It is not difficult to identify the optimal cross-section, but the proposal is not sufficiently detailed to determine the optimal arrangement of ribs inside. Here, an auxiliary model (Fig. 5) can be used for the optimization of the rib arrangement (Harzheim and Graf 2002). The idea of this model is that, usually, only the edges of ribs are highly loaded, and that this area determines the optimal arrangement. Consequently, it should be sufficient to apply topology optimization only to the edge area. Using this idea, a model of the cross-section only is created. This is closed at the open side, with a layer of shells (layer 1), which has the same grid point arrangement as the elements at the bottom of the cross-section. This shell

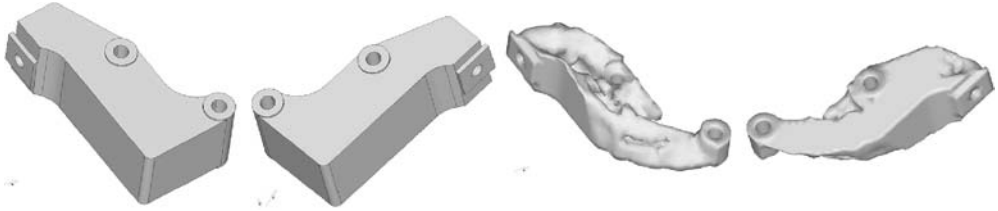

Fig. 4 Two views of the design space for an engine bracket (*left*) and the smoothed design proposal resulting from topology optimization (*right*)

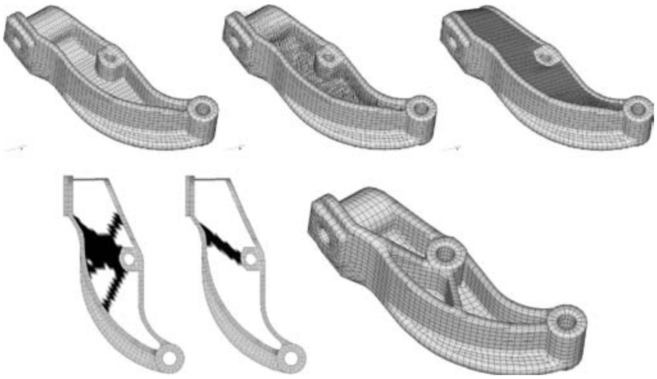

Fig. 6 *Upper row*: Structure of the auxiliary model for the bracket, from *left* to *right*: cross-section, model with added bars and complete model with shell layer, which closed the open side of the cross-section. *Lower row*: Design proposals resulting from the optimization of the auxiliary model with a large and a small volume fraction and the resulting final design

layer simulates the edge area of the ribs at which topology optimization will be applied. Additionally, the coupling of the rib edges to the bottom of the cross-section is simulated by connecting every grid point of the shell layer with the corresponding grid point of the cross-section bottom with a rigid bar element. Finally, a shell layer (layer 2) is added on the bottom to couple the rotational degrees of freedom as well. Usually, the topology optimization of the auxiliary model leads to framework-like structures in the shell layer, which reflect the optimal rib arrangement. Figure 6 shows the result for the engine bracket for two different volume fractions. One rib can be derived from the proposal with the small volume fraction, whereas the other proposal gives an indication for two additional ribs. Because of manufacturing constraints, only one of these two ribs could be included in the final model. The analysis of the final design shows that the stresses are not critical, and that the bracket fulfills all requirements.

It should be noted here that it is remarkable that the upper rib, which results from the proposal with the small volume fraction, does not run to the center of the screw hole but touches it tangentially. We checked the alternative and found

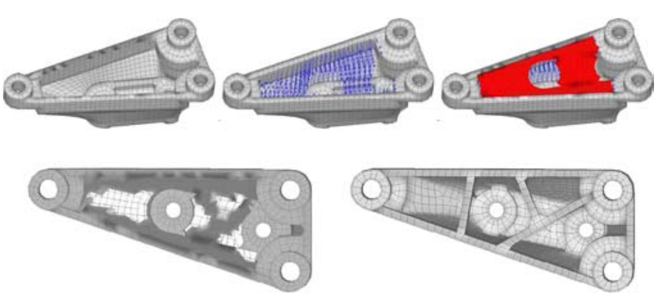

Fig. 7 Determination of the optimal rib arrangement for an engine bracket. *Top*: Structure of the auxiliary model, from the left: Empty bracket, bracket filled with bars and bracket closed with a shell layer. *Bottom*: Proposal for the rib arrangement after applying topology optimization and the resulting final bracket

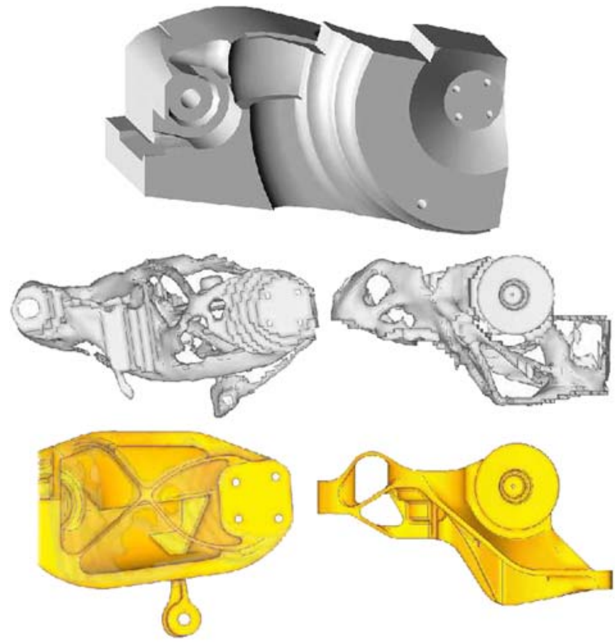

Fig. 8 Topology optimization of a control arm of a rear axle: The design space (*top*), two views of the smoothed proposal resulting from an optimization run with SKO (*middle*), and two views of the final design (*bottom*)

that this arrangement is really better with respect to the stress level.

An additional example for the optimization of a rib arrangement of an engine bracket is shown in Fig. 7. This

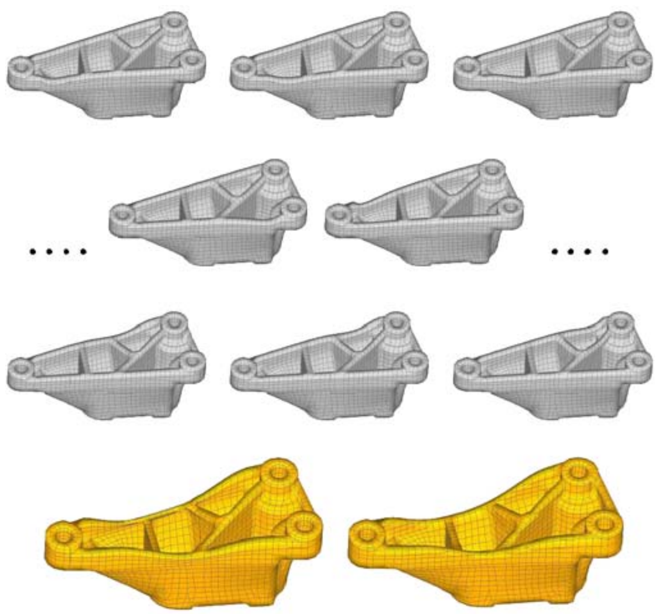

Fig. 9 Shape optimization of the engine bracket of Fig. 7. The *upper three rows*: show 8 of 18 shape basis vectors generated with SHAPE200. The resulting optimized design is shown on the *left side* in the *lower row*. It is seen that the optimization reached the limit in the variation of the shape, and that a creation of a new mesh was necessary to confirm the result (*right side*)

bracket has been shape optimized afterwards, as described in the next section.

However, the auxiliary model cannot be used for all problems. An example is shown in Fig. 8, where the proposal has a very framework-like structure. Here, the interpretation of the design proposal is very difficult and it is obvious that a feasible cast part can only be created by going very far away from the proposal. Furthermore, the modeling of an auxiliary model is very difficult here because it is hard to recognize a cross-section structure.

Even if the auxiliary model does not work for all problems, it can still be used for many components.

3.6 Fine-tuning using shape optimization

A real big problem is the fine-tuning of a cast part. The most simple optimization task is to find the optimal thickness of ribs and walls. This can be done with minimum effort using a shell model because then we have an ordinary sizing problem. However, for strength problems, a solid model is required to compute the stresses with the desired accuracy. For a complicated cast part, neither the CAD nor the FEM approach is able to create the shape variations for the wall thickness, at least not in an acceptable time frame. This may be changed if the morphing tools become better. Here, the first approaches are promising, but also show that mesh deformations can occur very quickly for local shape variations, such as the variation of the thickness of a wall. Here, it is necessary to include a re-meshing algorithm to make it applicable in practice.

Global shape variations are much easier to create, as shown in the example in Fig. 9. Here, the FEM approach of solution 200 of MSC-Nastran (MacNeal Schwendler Corporation 1994) is used, and the program SHAPE200 (Harzheim and Graf 1997) has been applied to create the required shape basis vectors. The optimization problem was to minimize the weight subject to stress constraints to ensure the strength. The obtained weight reduction was 7%.

Summarizing, we have to realize that the fine-tuning capabilities are very limited today, and only global shape variations are practicable.

4 Summary and outlook

In this first part, we focused on the application of original topology optimization codes for the optimization of cast parts. Here, the determination of the optimal features of cast parts is the central theme, because the whole optimization potential is only available if they are included in the design. Topology optimization is a tool to compute these features, and, consequently, it plays a major role in the optimization of cast parts. The problem in the application is that only rough proposals can be computed, which are sometimes difficult to interpret and which are not good enough to show details. For the determination of rib arrangement, an auxiliary model has been presented which often helps. However, this approach requires an additional effort in modeling and computing. Furthermore, there are sometimes extremely hollow and framework-like structures, where the auxiliary model is not applicable. Also the problem of fine-tuning using shape optimization has been briefly discussed. In the second part of this two-review paper, we will show that the situation is improved drastically if manufacturing constraints for cast parts are included in the optimization algorithm.

References

Altair Engineering, Inc (1999) OptiStruct user's manual, version 3.5. Troy, MI

Altair Engineering, Inc (2002) OptiStruct user's manual, version 5.1. Troy, MI

Baumgartner A, Harzheim L, Mattheck C (1990) SKO (Soft Kill Option): the biological way to find an optimum structure topology. Int J Fatigue 14:387–393

Bendsoe MP (1989) Optimal shape design as a material distribution problem. Struct Optim 1:193–202

Bendsoe MP (1995) Optimization of structural topology, shape, and material. Springer, Berlin Heidelberg New York

Bendsoe MP, Kikuchi N (1988) Generating optimal topologies in structural design using a homogenization method. Comput Methods Appl Mech Eng 71:197–224

Fuchs MB, Paley M, Miroshny E (1999) The Aboudi micromechanical model for topology design of structures. Comput Struct 73:355–362

Harzheim L, Graf G (1995) Optimization of engineering components with the SKO method. Proceedings of the ninth international conference on vehicle structural mechanics and CAE, April 4–6, 1995, Troy, MI, pp 235–243

Harzheim L, Graf G (1996) Shape and topology optimization in automotive industry. Proceedings of the 3rd international conference on high performance computing in automotive industry, October 7–10, 1996, Paris, pp 167–182

Harzheim L, Graf G (1997) Shape200: a program to create basis vectors for shape optimization using solution 200 of MSC/NASTRAN. Proceedings of the X international conference on vehicle structural mechanics and CAE, April 8–10, 1997, Troy, MI, pp 219–228

Harzheim L, Graf G (2002) TopShape: an attempt to create design proposals including manufacturing constraints. Int J Veh Des 28:389–409

Harzheim L, Graf G, Klug S, Liebers J (1999) Topology optimisation in practice. ATZ Worldw 7–8:11–18

Hassani B, Hinton E (1998) A review on homogenization and topology optimization: I. Homogenization theory for media with periodic structure. II. Analytical and numerical solution of homogenization equations. III. Topology optimization using optimality criteria. Comput Struct 69:707–756

Hinton E, Sienz J (1993) Integrated topology optimization. In: Smith I (ed) Proc. of 2nd ACME Conf., Manchester

Ma Z-D, Kikuchi N, Cheng H-C, Hagiwara I (1992) Topology and shape optimization technique for structural dynamic problems. Recent Adv Struct Mech—ASME PVP-Vol. 248/NE-Vol. 10:133–143

MacNeal Schwendler Corporation (1994) MSC/NASTRAN design sensitivity and optimization, version 68

Mattheck C (1990) Design and growth rule for biological structures and their application in engineering. Fatigue Fract Eng Mater Struct 13:535–550

Mlejnek HP, Schirrmacher R (1993) An engineer's approach to optimal material distribution and shape finding. Comput Methods Appl Mech Eng 106:1–26

Olhoff N, Ronhold E, Scheel J (1998) Topology optimization of plate like structures using 3-D elasticity and optimum 3-D microstructures. Proc. 7th AIAA/USA/NASA/ISSMO symposium on multidisciplinary analysis and optimization, St. Louis, MO, pp 1853–1863

Pederson P (1998) Influence from non-linearities on optimal shape design. 7th AIAA/USAF/NASA/ISSMO symposium on multidisciplinary analysis and optimization, Part 2, 1998, pp 1123–1130
Pederson P (2000) On optimal shapes in material and structures. Struct Multidiscipl Optim 19:169–182
Rozvany GIN, Bendsoe M, Kirsch U (1995) Layout optimization of structures. Appl Mech Rev 48:41–119
Xsi YM, Steven GP (1993) A simple evolutionary procedure for structural optimization. Comput Struct 49:885–896
Yang RJ (1997) Multidiscipline topology optimization. Comput Struct 63:1205–1212
Young V, Querin OM, Steven GP, Xie YM (1999) 3D and multiple load case Bi-directional Evolutionary Structural Optimization (BESO). Struct Optim 18:183–192
Zhou M, Rozvany GIN (1991) The COC algorithm: Part II: topological, geometrical and generalized shape optimization. Comput Methods Appl Mech Eng 89:197–224