Recent improvements in topology and shape optimisation and the integration into the virtual product development process

Dr.-Ing. Ralf Meske\textsuperscript{1}, Dr.-Ing. Jürgen Sauter\textsuperscript{1}, Dipl.Ing. Zeynel Güngör\textsuperscript{2}

\textsuperscript{1}FE-Design GmbH, Karlsruhe, Germany, www.fe-design.com
\textsuperscript{2}Dr.Ing. h.c. F. Porsche AG, Weissach, Germany, www.porsche.com

1. Introduction

Due to the demand to decrease the time-to-market of new products while maintaining a high quality level and reducing overall product development costs, structural optimisation tools have become of significant importance in the virtual product development process. These tools like topology and shape optimisation have reached wide spread acceptance as stand-alone applications in the CAE environment, but a closer integration in the product development chain is still desirable. To achieve this, FE-Design is leader of a subproject with industry partners like Porsche, Audi, Bosch and Keiper within the German research project “Integrated Virtual Product Creation”.

FE-Design offers with the optimisation system CAOSS an integrated solution for structural optimisation. CAOSS is successfully used in industry with an interface to MSC.Nastran under the product name MSC.Construct since 1997. Now, FE-Design has developed further interfaces to the solvers ABAQUS, ANSYS, IDEAS and MSC.Marc. Structural optimisation of real-world problems was up to now limited to linear analysis only. With the interfaces to the non-linear solvers ABAQUS and MSC.Marc it is now also possible to perform structural optimisation with moderate non-linearities.

After an introduction into the optimisation system CAOSS the integration of the structural optimisation into the development process is shown. Then an application of shape optimisation with hyperelastic material from the company Freudenberg is given. It follows an example for topology optimisation with contact boundary conditions. Finally an industrial applications of topology optimisation using MSC.Construct at Porsche is presented.
2. The Optimisation System CAOSS

CAOSS is a system for non-parametric structural optimisation. CAOSS can perform topology and shape optimisation of FE models with an arbitrary number of boundary conditions and load cases. A parameterisation of the model is not necessary. The optimisation algorithms are based upon mechanical optimality criteria.

Structural optimisation with CAOSS is an iterative process. The structural response of the component is calculated in each iteration with an external FE solver. The high quality of the results is guaranteed by using approved and accepted industry standard solvers. Further benefits for the user are that he can work with his favourite solver and that he does not need additional training for a new solver. Already existing FE models can be used directly in the optimisation.

CAOSS is successfully used in industry with an interface to MSC.Nastran under the product name MSC.Construct since 1997. Now, FE-Design has developed further interfaces to the solvers ABAQUS, ANSYS, IDEAS and MSC.Marc.

The optimisation procedure with CAOSS is sketched in Fig 1. The optimisation task is defined in addition to the already known FE preprocessing in an optimisation preprocessing step. This can be just the definition of node or element groups to specify the optimisation domain, but also allows the definition of manifold constraints for the optimisation task. The result of this step is a compact parameter file to control the optimisation. The optimisation itself is performed in an iterative process between CAOSS and the FE solver. In each cycle CAOSS reads the results of the FE calculation and modifies the FE input file according to the objective function of the optimisation task until the convergence criterion is satisfied. The result of the optimisation can be visual-
ized with most common FE-postprocessors and is available in various formats for the further processing in the virtual product development process.

The actual version CAOSS 4.0 has the following features:

General capabilities:

- Stable and fast optimisation algorithms based on optimality criteria
- Efficient handling of very large models (up to 4.5 Mio dofs)
- Optimisation with an unlimited number of load cases

Topology optimisation:

- Maximization of the stiffness with displacement constraint
- Maximization of the stiffness with volume constraint
- Maximization of the first natural frequency
- Definition of frozen, initial and priority domains as design variable constraints
- Output of iso-surfaces as VRML, STL or FE-surface mesh

Parameter less shape optimisation:

- Minimization of the equivalent stress due to various stress hypotheses
- Maximization of the first natural frequency
- Extensive capabilities for the definition of constraints (restriction of the optimisation domain, coupling of nodal degrees of freedom, volume constraints, etc.)
- Mesh adjustment and mesh smoothing in each optimisation cycle

In combination with the non-linear solvers ABAQUS or MARC the following features of the solvers can be used:

- Shape: All linear and moderate non-linear materials
- Topology: Isotropic, linear-elastic material
- Large deformation
- Contact definition outside and at the boundary of the optimisation domain
- Nearly all continuum elements are supported in the optimisation. The remaining elements can be used outside the optimisation domain.

An essential focus of the optimisation system CAOSS is the integration of the structural optimisation in the virtual product development process. For the continuous improvement of this integration several activities together with end-users, software companies and research institutions are in progress, which will be presented in the following section.
3. The German Research Project Integrated Virtual Product Creation

New competitive products must meet the growing demands of the market. They must be light-weighted, resource efficient, durable, stable, and must have a low noise emission. At the same time, the product must be introduced quickly into the market. For the fulfilment of these demands it is necessary to use structural optimisation tools besides established CAE, CAD, DMU, and PDM systems. The functionality, the handling and especially the integration and correlation with other tools of the virtual product development process are determining factors.

Within the framework of the German research project “Integrated Virtual Product Creation” (iViP) innovative technologies for structural optimisation will be integrated into the process chain in the subproject 3.3 “Integrated shape and topology optimisation in the design process”.

In project 3.3 innovative and easy to use tools will be developed. These tools will allow the integrated topology and shape optimisation in the design process. The latest technological developments are integrated in the process chain CAD → simulation → topology optimisation → shape optimisation → CAD. Different developments in the area of structural optimisation will be combined and broadened according to user demands, so that this tool will not only be useable by the analysis specialist but also by the designer. A unique feature of project 3.3 is the close link between software developers, research institutes, and five end users of various industries (see Fig 2).

![Fig 2: Partners in project “Integrated shape and topology optimisation in the design process”](image)

The integration of the topology and shape optimisation in the design process is shown in Fig 3. The process consists of several steps. The first step is the definition of the design space in the CAD system, the second step the mesh generation in the FE preprocessor and the specification of the optimisation task in the optimisation preprocessor. The topology optimisation follows...
Recent improvements in topology and shape optimisation and the integration into the virtual product development process as next step. In contradiction to the classical design approach here only the available design space has to be defined. The topology optimisation distributes the material automatically according to the given objective function and the prescribed constraints. With this approach components are created quasi “out of nowhere”. The result of the topology optimisation is a design proposal which consists of a set of connected elements and is not geometry based. This structure has to be transferred into a smooth structure in the next step. Here, a remodelling due to manufacturing constraints may take place, as well. Afterwards, an additional shape optimisation can be performed to minimized local stress concentrations. At the end of the optimisation process, the optimised design is converted in a geometry based CAD model, which can be led back into the manufacturing process by the familiar interfaces.

**Fig 3: Integrated shape and topology optimisation in the design process**

An efficient and easy to use optimisation tool, which is completely embedded in the process chain, is developed in the project “Integrated shape and topology optimisation in the design process”.
4. Shape Optimisation of a Hyperelastic Support

A substantial amount of the developed parts at the Freudenberg Group are rubber-metal components. The computation of rubber components inhibit in general several non-linearities. Because of the large deformation geometric non-linearity has to be taken into account. Due to the incompressibility of the material hybrid elements have to be used. The hyperelastic material law itself is non-linear. Sometimes contact problems occur, which lead to non-linear boundary conditions. These complexities imply that accurate calculations for these components can only be performed with a solver like ABAQUS which is specialized for non-linear problems.

The Freudenberg Group has been using CAOSS together with MSC.Nastran for structural optimisation for several years. Extensive investigations of a semi-automatic linearized optimisation with MSC.Nastran using a linear-elastic material as substitute have been made, but did not lead to an acceptable result both in accuracy and performance [2]. Therefore, there was a strong interest to perform the optimisation with CAOSS in combination with ABAQUS.

Due to the integration of ABAQUS in the optimisation with CAOSS the user now can take advantage of the analysis capabilities of ABAQUS in the optimisation process with CAOSS. The shape optimisation of the following example of an hyperelastic support was performed without difficulties in the same way as with a linear-elastic material. The hyperelastic material behaviour was modelled in this case with a Neo-Hooke model. The initial configuration of the component is shown in Fig 4 on the left side. Due to the symmetry of the component only the right half was modelled. The component is fixed on the lower right side. In the radius there is a steel ring which is not shown in the figures. A tension and compression load in y-direction was applied on the steel ring. The compression load led to a folding of the component in the initial design, which had a negative influence on the life span.

![Initial design](image1.png) ![Optimized design](image2.png)

Fig 4: Equivalent stress and geometry of the hyperelastic support
The nodes on the lower left contour of the component were chosen as design nodes of the optimisation. The optimisation target was the minimization of the von Mises equivalent stress along the design nodes. Because the total stiffness of the component should not be changed too much, a constant volume constraint was defined. The optimisation yields a significantly improved design after 10 optimisation cycles. The modified geometry is shown together with the maximum equivalent stress of both load cases in Fig 4 on the right side. The deformation of the initial and the optimised component is shown for both load cases in Fig 5. The maximum equivalent stress was reduced in both load cases for 26% each. The folding of the component in the compression load case was prevented by the geometry change.

Further potential in the shape optimisation is seen from Freudenberg in the optimisation with user defined material laws. Due to the modular structure of CAOSS it is possible to use own material laws in the FE calculation as long as correct stress values are calculated for the optimisation. This will be subject of further investigations together with Freudenberg.
5. **Topology optimisation with non-linear boundary conditions**

The exact boundary conditions can very often not be given exactly during the design process of a new component. Non-linear boundary conditions may occur due to contact problems. These boundary conditions can only be transformed into equivalent boundary stresses with a high effort and loss of generality. Therefore it is desirable to allow general contact definitions at the boundary of the optimisation domain in structural optimisation.

Due to the integration of CAOSS and ABAQUS this is now possible for the ABAQUS users in the usual way. The user creates an analysis model for ABAQUS with the required contact definitions. Afterwards he defines the optimisation task. Because of the modular structure CAOSS does not need to know the existence of the contact definition. The contact problem is implicitly included in the optimisation by the contact forces and the resulting stresses. Thus the user can take full advantage of the capabilities of ABAQUS in contact calculation.

As an example for a topology optimisation with contact an optimisation of a tension/compression connecting rod is presented. The FE-mesh of the available design space for the connection rod and the FE-mesh of the bolt is given in Fig 6. The lower and the left boundary are symmetry boundaries. The centre of the bolt is loaded in two load cases with a force of equal magnitude in positive and negative x-direction. A node-element contact is defined between rod and bolt. The boundary of the bolt with the coarse mesh is the master surface, the boundary of the rod with the fine mesh is the slave surface.

![Fig 6: 2D connection rod and bolt with different mesh size and contact definition.](image)

The optimisation target was the maximization of the stiffness with a volume reduction of the rod to 50%. No restrictions were assumed for the elements at the contact surface, hence a material reduction at the contact surface was admissible. The optimised material distribution is shown in Fig 7.
Recent improvements in topology and shape optimisation and the integration into the virtual product development process.

Fig 7: Optimized 2D tension-/compression conrod (50% volume reduction, 16 iterations)

The optimisation yields a material distribution along the upper side of the connection rod. The compression force from the second load case is introduced diagonally into the arm of the rod while the load at the middle line is reduced. Therefore less stress is transferred via the contact surface at the middle line and material is removed in this area. As a result, the optimised design has a void area directly at the contact surface. A second smaller void area is created further along the circumference.

This example shows impressively the potential of topology optimisation with contact boundary conditions. A reorientation of the flux of the contact forces happens during the optimisation. This change of boundary conditions is only possible with contact conditions and not with prescribed boundary stresses as equivalent load. If it is not wanted due to design reasons to have void areas at the contact surface, the user can take this into account at the beginning of the optimisation. In this case all elements at the contact surface can be defined as “frozen elements”, causing the material density to remain unchanged during the optimisation.

After the capabilities of the topology optimisation with contact conditions have been shown successfully for 2D, the application to 3D will be demonstrated in the following example. The conrod and the bolt of the above example were extruded in the 3rd dimension, which gave a model with about 25000 elements and 29000 nodes. The surface at z=0 was defined as additional symmetry plane.

A contact surface was defined between the rod and the bolt with 1000 contact nodes on the slave surface. Tension and compression forces of equal magnitude were applied in two load cases at the outer node on the middle axis of the bolt, which resulted in a slight bending of the bolt.
Recent improvements in topology and shape optimisation and the integration into the virtual product development process.

The goal of the optimisation was the maximisation of the stiffness with a volume reduction to 40%. The first element layer at the contact surface was defined as “frozen” area, hence void areas at the contact surface were not admitted. The result of the optimisation is shown in Fig 9. It is similar to the 2D example. Due to the loading conditions the material is distributed further towards the point where the forces are applied.

Fig 8: 3D connection rod and bolt with different mesh size and contact conditions.

Fig 9: Optimised 3D tension-/compression conrod (40% volume reduction, 20 iterations)
6. Topology Optimisation at Porsche

The application of structural optimisation in the development process has become an increasing importance for the company Porsche. Both topology and shape optimization for linear statics with MSC.Construct are used.

The first step in the development of a new component is the determination of the approximate shape with a topology optimisation. In dependence of the boundary conditions and the maximum available design space, a design concept is sought which is as light as possible but still satisfies all requirements with respect to strength and stiffness. The result of the topology optimisation is the basis for the design proposal of the designer. This design is further improved with respect to stress and weight by an additional shape optimisation.

As an example the topology optimisation of a boot plate is shown in Fig 10. After the determination of the available design space, frozen areas were defined which must not be changed during the optimisation. The component is loaded with a torsional moment and fixed with six screw joints.

![Fig 10: Topology-optimisation of a boot plate](image_url)
At first, an optimization with a coarse model with 43000 degrees of freedom was performed. The results were useful, but needed to be interpreted. The following optimisation with a significantly refined model with 370000 degrees of freedom gave expressive and definite results. Afterwards a smoothing of the surface was performed with MSC.Patran.

7. Conclusions

The use of structural optimisation tools in the early stage of the development process offers new potential in the process chain. The development process becomes faster and more efficient by using topology and shape optimisation. This results in structures which are lighter, stronger and more durable which constitutes a competitive advantage for the companies that use this solutions.

The optimisation system CAOSS provides an integrated solution for structural optimisation of real-world problems. It has reached wide spread acceptance in industry and offers interfaces to all major FE-solvers. With the interfaces to the non-linear solvers ABAQUS and MSC.Marc it is now also possible to perform structural optimisation with moderate non-linearities.

8. References

The listed publications are available as download from www.fe-design.com.


