Automatic Shape Optimisation of Elastomeric Products

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1. Introduction

In increasing international competition, technologically oriented companies can only survive, if they can also provide cost efficient products as well as a high technological innovation strength. Therefore, in modern development philosophies, like "Simultaneous Engineering", the calculations engineer is more and more consulted in the conceptional phase of product development. Consequently, it is compellingly necessary in an effective procedure that all tools and data be placed at everyone's disposal. This way, everyone is better able to assist the conceptional design of new products as well as to make detailed improvements on already existing designs. Therefore, efficiently implemented optimisation algorithms complement the proven discrete calculation procedures (FEM, BEM) of mechanically loaded structures [1].

In structural mechanics, there are three levels of optimisation:

- Topology
- Shape
- Sizing

Topology optimisation, like that from Bendsoe and Kikuchi [2], has the capability to support the design level. Presently, for the industrial application of topology optimisation only a small number of commercial codes is available. The **shape optimisation** has been used for industrial applications for some time, but it is used to handle almost exclusively linear problem sets. The **sizing optimisation** is offered from almost every large FEM-package. It is industrially applied mainly for complex beam and shell structures.

While not as complex as the topology optimisation is, shape optimisation will be strengthened and widely applied in industry in the near future. This results from the necessity to apply a detail shape optimisation to already topology optimized components, too. In this paper the special case of shape optimisation for handling models with hyperelastic materials is focussed.

2. Software Requirements for Calculation of Hyperelastic Materials

For simulation purposes of rubber components, which often are highliy nonlinear problems, sophisticated software has to be provided. The requirements for solver and optimisation program are discussed more detailed.

2.1 FE Analysis Software

2.1.1 Fundamental Considerations

One of the main tasks of simulation techniques is to obtain results which are close to reality. This is one of the requirements for shape optimisation, too. For linear static analysis the main task often is to find the correct set(s) of loads and boundary conditions.

In FE calculations of elastomer components, we can see a big influence of the definition of the hyperelastic nonlinear material behaviour on the results. Therefore the decisive task for obtaining reliable results from the simulations on terms of failure and lifetime estimates as well as shape optimisation is a precise modelling of the material's behaviour for general threedimensional stress and deformation states. For failure analysis, the local stresses are the decisive factor. For this reason, Freudenberg has been developing appropriate material models for about seven years.

In comparison to metals, modelling the behaviour of elastomers is a considerably more complex task. The following physical and chemical phenoma have to be considered within the simulation (Fig. 1):

- **Quasistatic behaviour** (non-linear material behaviour, non-linear geometric behaviour)
- **Large local strain** (up to a few 100%)
- **Viscoelastic behaviour** (dependent on strain rate and frequency)
- **Influence of filler** (amplitude and preload dependency)
- **Influence of environment** (chemical medium, ageing phenomena)

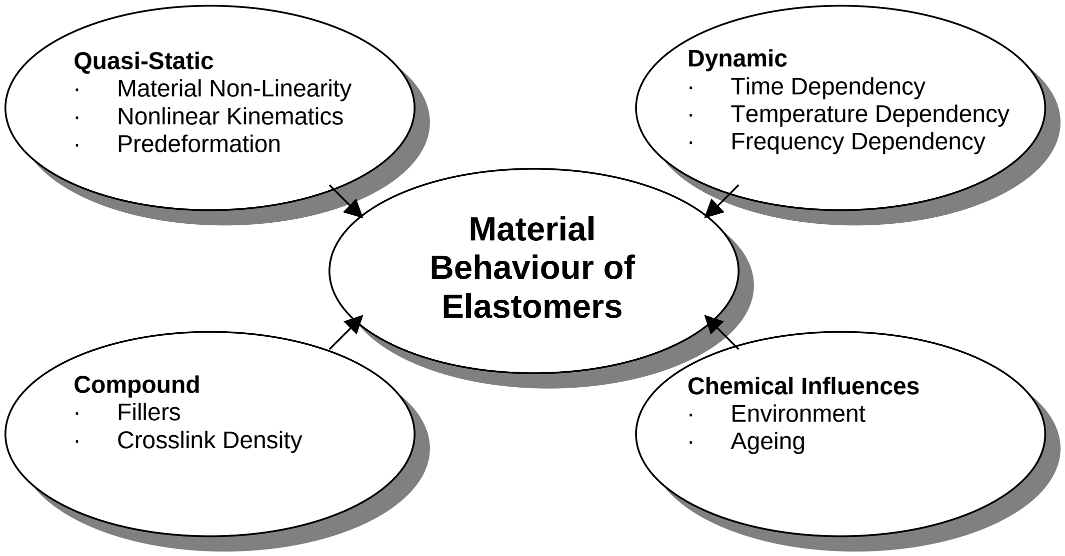


Fig. 1: Influences on the Material Behaviour of Elastomers

Often the local strains of the components are higher than 50% and therefore the material nonlinearity is to consider. However, not only the hyperelasticity and deformation history of the material are to be noticed but also the dynamic and viscoelastic effects play an important role for the elastomer calculations. Normally the dynamic properties do not only depend on frequency and amplitude but also on temperature. Besides, compared with metallic materials, the influence of chemicals (which the elastomeric component may be exposed to) has to be paid attention on.

The described physical properties make the numerical calculations very complex and place high demands on the applied program system. For an FEM program to be applied, the following properties must be considered for the calculation of elastomer components:

- Large component deformations require **geometric nonlinear** calculations
- Elastomers are characterized through their **incompressibility**

- The large elastic deformation in the component cause inevitably **a material nonlinearity**, by which the **hyperelasticity** of the material is substantial for quasistatic calculations
- The elastomer may **contact** with other components or with itself. In both cases, the influence of the **friction** would be important [7]
- For dynamic calculations the **viscoelastic material behavior** is relevant. For oscillating stress material laws are substantial which can grasp the **little amplitude by a large predeformation**.
- For life span and acoustic calculations, **modal analysis** and **transient calculations** are important
- For the optimisation of the production processes [8] and the simulation of self heatening caused by oscillating loads, **thermal analyses** are necessary.

Although stresses in most rubber components will involve a combination of all these phenomea, a factorisation approach is used. This is done firstly in order to verify the models concerned, but also to separate the effects of the individual phenomena to understand them.

Overall, the work entailed by the analysis of elastomer components is significantly higher than in the case of metals. Often there will be a combination of three different non-linearities.We always have to deal with material an geometric non-linearities, and often there also will be a structural non-linearity because of contact between different flexible and rigid bodies. Other complicating factors include the very complex physical material behaviour and an enormous variety of different materials.

In the rubber industry, the material concerned (together with the compounding and production) is still the most jealously guarded corporate know-how. Often, a new and improved material is developed due to a special problem. Therefore the material parameters for the simulations often are not available and have to be determined individually, entailing an extra experimental work. This is why characteristic values often are not published in the standard literature even if available.

In practice, this means that it’s essential for the models concerned to enable material parameters to be determined quickly and reliably in an affordable standardised test procedure. Therefore Freudenberg is developing special tests to examine the parameters quite efficiently at the same time as we are developing in-house material models.

For product development in many cases it is important to know the nonlinear static stiffness curve of the component. As in the use of many components appear large deformations due to the loads, in the FE calculations the geometric nonlinearities have to be considered, too. The good agreement between the measured and calculated curves (Fig. 2) is guaranted for every simulation through an applied hyperelastic material law developed by the Freudenberg Company [9] which is used for standard FE calculations.

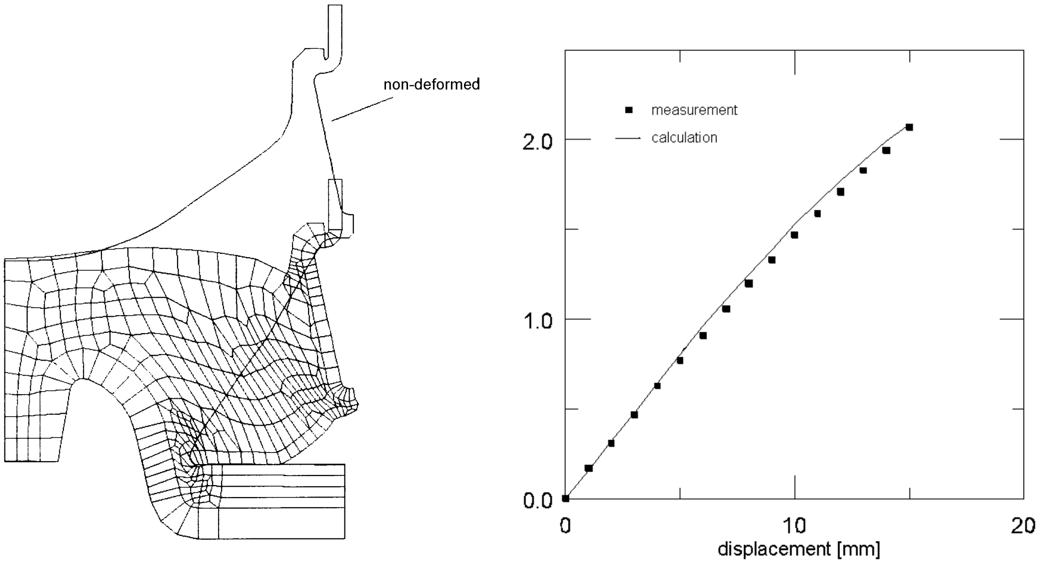


Fig. 2: Hydromount Spring: Comparison of Simulated and Measured Load-Deflection-Curve

2.1.2 Quasistatic Material Behaviour

The simplest model for elastomers is a physically based one, known as Neo-Hooke model. When we assume incompressibility for elastomers, which is a very good approximation, the material will be characterised by only one parameter - the shear modulus G. The Neo Hooke model, however, can be used with sufficient accuracy only for small to medium strains. Mooney's attempt to extend the Neo-Hooke model phenomenologically for large strain should be regarded critically:

„.. Thus, if we consider the extension and compression data together, it is clear that the Mooney equation is no improvement over the statistical theory; indeed it is very much less effective ..." [12]

Although Rivlin and Saunders had warned explicitly against a „naive" use of the Mooney model back in 1951, analyses are still frequently being carried out using the Mooney model. The reasons for this are to be found firstly in an inadequate knowledge of the material behaviour of elastomers. Compared to metals, this material has been considered under mechanical aspects only for a comparatively short time. Besides there is a lack of appropriate characteristic values and in many CAE departments rubber related simulations are performed analogously to FE simulations of metal components with FE codes frequently being especially designed for linear problems.The special knowledge of rubber as a material is largely confined to the developers of rubber components, but most of those people do not as yet possess the necessary special numerical knowledge. Furthermore, at smaller companies often neither the extensive experimental studies nor the relatively complex FE analyses can be done.

In higher sophisticated FE codes like MSC/NASTRAN, to supplement the Mooney-Rivlin model, elastomer models have been implemented in the form of polynomial theorems for the strain invariants (Rivlin approach). These exhibit the decisive disadvantage of simulating unreliable results as soon as the (mostly multi-axial) deformation state of the components concerned deviates from the (mostly unidirectional) deformation state in which the model parameters have been determined. For an accurate modelling of the extreme nonlinear elastomer behaviour, furthermore, higher order polynomials are required, which may cause numerical problems due to oscillations.

The Ogden model has been implemented in MARC to avoid these disadvantages involved in polynomial theorems. The Ogden model, however, is likewise a purely phenomenologial one, not based on physical phenomena. This results into a relatively large number of experiments to get the desired data. In the most frequent form of the Ogden model, the quasi-static behaviour of an elastomer is described by means of six different parameters. Also, the Ogden model requires a very wide fitting range in order to achieve reliable results. This means that using the Ogden model entails an expensive testing outlay and therefore a lot of costly testing.

At Freudenberg, a physically substantiated material model has been developed. This model permits elastomers to be caracterised precisely over a very large deformation range (). This model has been implemented as a user subroutine in ABAQUS, and is used as a standard feature for all nonlinear FE calculations. MSC/NASTRAN unfortunately at this time doesn’t provide the possibility to enclose user subroutines for the description of the hyperelastic material behaviour. Therefore for optimisation purposes we have to use the Neo-Hooke model, which is only valid for small strains.

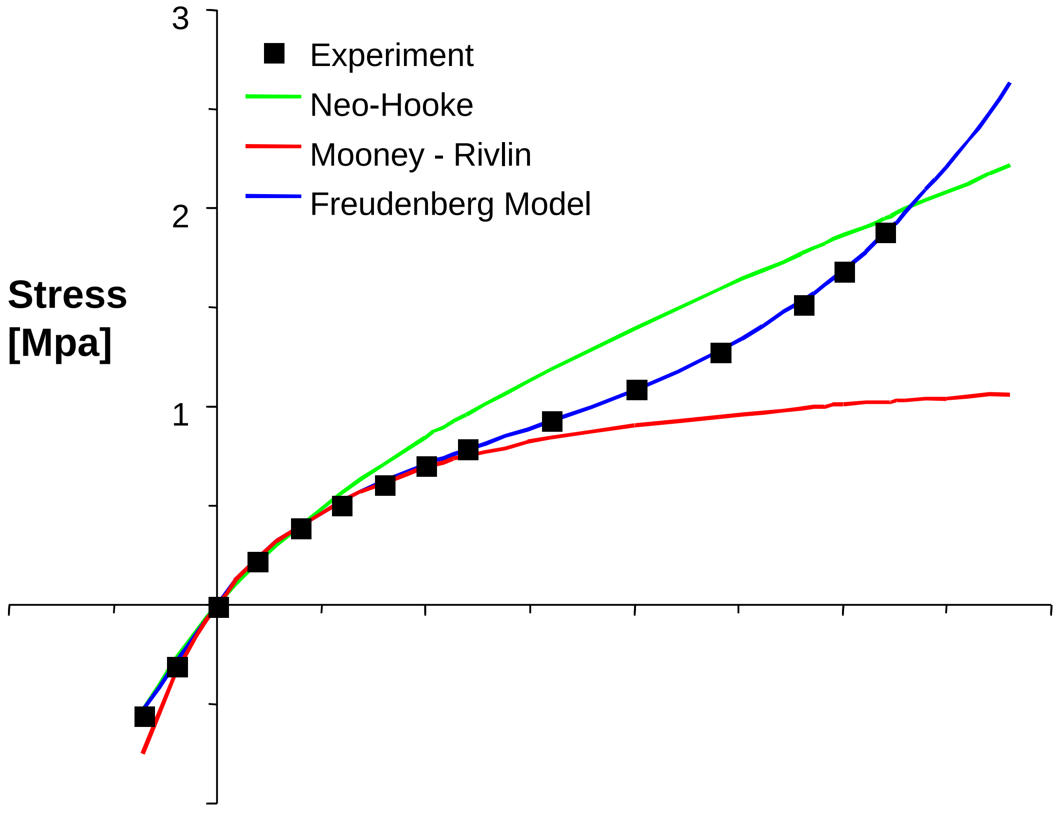


Fig. 3: Comparison of Different Material Models

2.2 Optimisation Software

The commercial success of the automated optimisation depends ultimately on the acceptance of the procedure by the industry's calculation engineers and design departments. Research work by participating universities and research institutes to develop and improve optimisation methods can only be financed long term if the results will be quickly and efficiently converted into tools that make it possible to leap ahead of the competition. Therefore, one must begin to analyze every research project keeping in mind the requirements of later customers.

System suppliers will increase to decisive development partners of the automotive industry and thus, a relatively large customer potential for such optimisation programs. Their resources and their structure [3] distinguish the supply industry quite distinct from their own customers, the automotive industry. For this reason a typical request profile should be worked out for the shape optimisation from the point of view of these potential regular customers. In this case particularly the utilization for elastomer calculations must be guaranteed:

- Optimal solution ⌠ Better solution

In academic circles, optimal solutions are often discussed, i.e. about their principal existence, and above all how could be found global as well as local optimum points. Often the shape optimisation is drawn up for existing designs, whereby the initial design could already disqualify the global critical point. However in practice, it is often sufficient to find as fast as possible a **better solution** where the demands on the component will be directly met. Only for conceptional designs in the predevelopment phase should **optimal solutions** be searched, or in this case, topology optimisation should have been applied earlier as the shape optimisation.

- Nonlinear problem sets ⌠ Processing time

On rubber and metal hybrid components, demands on the base life span will increase, which will push the used materials until the limits of their load capacity [4]. The numerical representation of such components is quite complex because the numerical simulation must often contain a **triple nonlinearity** (structural, geometrical, and material nonlinearity). These problems increase the already high demands on the hard and software and often result in much longer processing times. Because shape optimisation problems are solved iteratively it must be taken in account that on the one hand the software is able to handle nonlinear problems and on the other hand a solution is found within a very small number of iteration loops. Only then it is possible for the calculations engineer to prepare an improved component design within an acceptable **processing time**.

- Efficiency of the procedure ⌠ Time for problem solution

The development cycle for elastomer components has to be reduced more and more. Therefore the period of time for design studies of detailed problems will have to be minimal, too. The problem solution does not only contain the solution of the optimisation problem, but also the definition of the optimisation model, the evaluation of the results, and its conversion into a constructable model. For the shape optimisation, the total time for the solution of the problem must be minimized. Therefore it is decisive the **time for the whole problem solution** and not only the **efficiency of the optimisation procedure**.

- Resources: Users and Software

In contrast to the large calculation department in the automotive industry, there are no specialists in the stamped supply industry which work exclusively on optimisation problems. Therefore, the **effective application** on the optimisation software should not depend on an correct special knowledge about the function of the algorithms. To reduce software cost and to increase the acceptance it is necessary that the **optimisation software** may be connected to already known FE codes. This makes it possible to proceed working in the user known environment. As the hardware cost will always be less important to the personel cost in comparison, it is more important to have the stability and toughness of the solution algorithms for a large amount of problems as to have a filed out convergence for fewer special cases.

· Optimisation model: Target function und boundary conditions

In optimisation purposes mostly many different load cases have to be taken in account. That requires that the **target function** can take into consideration different load cases simultaneously. An **interdisciplinary optimisation** is also useful. In this case the optimal structure can already fulfill every substantial static, dynamic, and thermal boundary condition through a suitable choice of restrictions. So separated proof calculations for these areas are not necessary anymore [5]. In any case **production technological boundary conditions** must also be ascertainable.

At the Machine Design Institute of the University of Karlsruhe, an approach has been developed for shape optimisation. The basic principle is a controller which, dependent on the load, moves rapidly towards an optimum component via feedback. For this, new optimum criteria were developed from the area of mechanically loaded components, which are based on the works from Baud, Neuber, Schnack, and Mattheck.

The basic principle of the restriction is very simple. The input parameters are the local node coordinates and the local node stresses. The output parameters are the local node modifications of the node coordinates. The controller reduces the surface curvature by applying mass (growing) at points with high stresses. For low stresses the surface curvature ist increased by removing mass (shrinking) at these points. Through the evaluation of the component surface and the corresponding geometry change, one receives after fewer cycles a minimally loaded surface contour. In the restricted algorithms, the knowledge is included about the implicit physics of the problem. The disadvantage is that for every problem group, a different control algorithm must be developed. Therefore a generally acceptable application is not possible. Also the input is realizable for only a limited extent of the restrictions and explicit target functions [6].

The program system MSC/Construct-Shape is based on this strategy. MSC/Construct-Shape is an additional module for MSC/NASTRAN for shape optimisation of components. In combination with the optimum criteria regarding the load minimum, very fast and capable algorithms have been developed which execute a shape optimisation based on not parameterized FEM models [10], [11].

2.3 Concepts for Optimisation of Elastomeric Components

In many cases the rubber components are loaded with an oscillating dynamic load. For the optimisation time to stop within reasonable bounds, the exact dynamic load of the component is applied through a static load. With help from FEM simulations and analytic inspection to the damage of the component, the life span determinant load is identified from the given load collective and taken into consideration for the exact optimisation process. The influence of the viscoelastic effects of the component optimisation is not substantial and therefore neglected in the calculation.

For the automatic shape optimisation, different manufacturing boundary conditions have to be considered:

- The elastomers must be joined to the metal component meeting construction guidelines of the Freudenberg Company
- The geometry of axisymmetric components must remain axisymmetric after the optimisation although non-axisymmetric loads are applied.
- Because the function is to secure, the component is also mounted in the previous building group (this is normally guaranteed because the geometry of the metal component during the optimisation remains fixed)
- The stiffness of the component during the optimisation should not change considerably (this restriction is, however, not to realize explicitly. Because only relatively small volume changes will be forced through the optimisation, this demand mostly is fulfilled implicitly)

2.3.1 Linearized Solution Concept

In order to minimize the total time for the shape optimisation, the linearized solution concept is applied (Fig. 4).

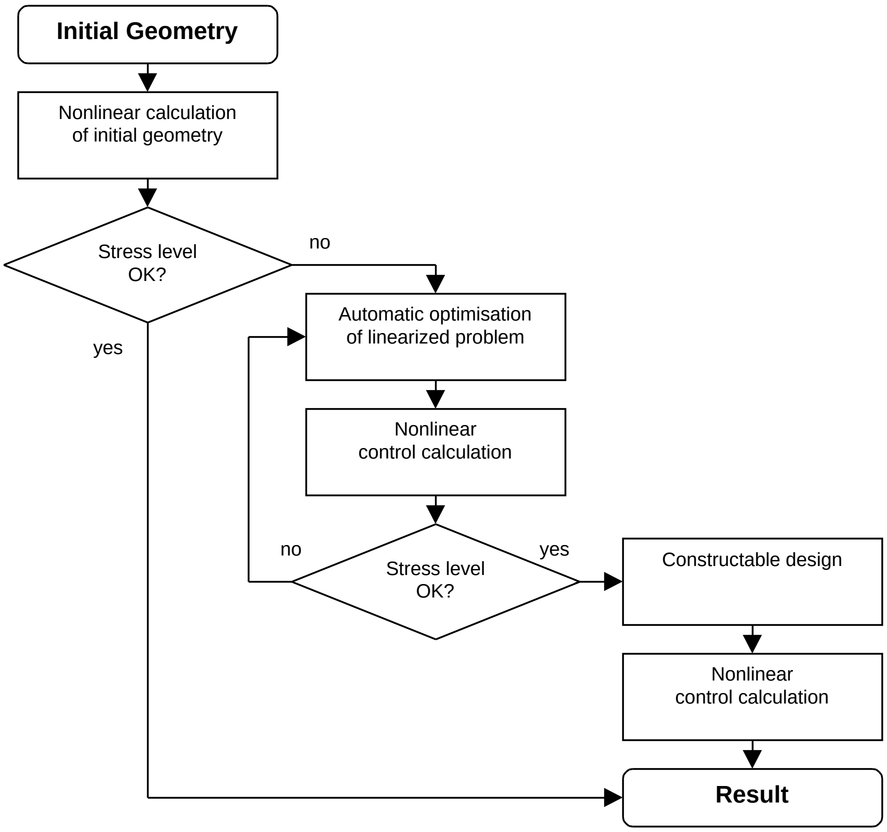


Fig. 4: Linearized Solution Concept

In a first step the initial design developed by the concept engineer is calculated with all relevent nonlinear boundary conditions (e.g. material and geometric nonlinearity). Similar to the procedure used in sequential linearization of mathematical approaches the real starting point is linearized in that way that with combination of different loads a load state adequate to the real one is generated. This linear problem is analized with MSC/NASTRAN and shape optimized with MSC/CONSTRUCT. In a third step a control calculation of the optimized design is done. With the feedback of the design engineers those steps have to be done several times. As MSC/CONSTRUCT is a FE based nonparametric shape optimisation program which generates directly the new node coordinates of the model, it is necessary as a last step to create a geometry corresponding to the issue directives of the design department for the CAD system.

2.3.2 Optimisation of Nonlinear Models

Now, with release MSC/CONSTRUCT V3.0 and MSC/NASTRAN V70.6, for the first time it's principally possible to use hyperelastic materials for shape optimisation within the optimisation process. Actually the first calculations and optimisations are done with this option.

It’s necessary to optimize the nonlinear problem set if it’s not possible to find a load combination adequate to the real one. Therefore geometric and material nonlinearities as well as contact have to be considered. As the CPU time for nonlinear problems increase drastically in comparison with the linear calculation, the need of efficient algorithms increases.

We also have to consider that the implemented material models in MSC/NASTRAN are not suitable for calculations with very high strains. At this time, the comparison of the results with a reference solver providing the use of more accurate material models is necessary. If the validity of the nonlinear results is guaranted, it is possible to use MSC/NASTRAN and MSC/CONSTRUCT for the optimisation of the nonlinear problem set.

3. Optimisation Examples

3.1 2D Optimizaton of an Elastomer Supporting Structure

3.1.1 Model and Boundary Conditions

The first example is a rubber supporting structure which is a typical example for 2D automatic shape optimisation with MSC/Construct-Shape. As it is an extruded structure, it is possible to generate the model as 2D plane strain model to reduce CPU time. First, relevant boundary conditions regarding the component calculation and shape optimisation have to be identified. For this example the critical oscillating load is modeled as two differend load cases in vertical direction. The task is to reduce the folding of the structure and to reduce maximum stresses which both will result in an increase of the life span.

3.1.2 Optimisation Results

Fig. 5 shows the scaled stress distribution of the initial design developed by the design engineers and the stress level of the optimized design which is already changed to a constructable solution.

Fig. 6 compares the different geometries of initial and optimized design. The difference of the two designs is very small, but the effect on the maximum stress level is very high. In the testing it could be shown that life span increased about 30%. This is a result of the reduced maximum principal stresses as well as the reduced folding of the structure.

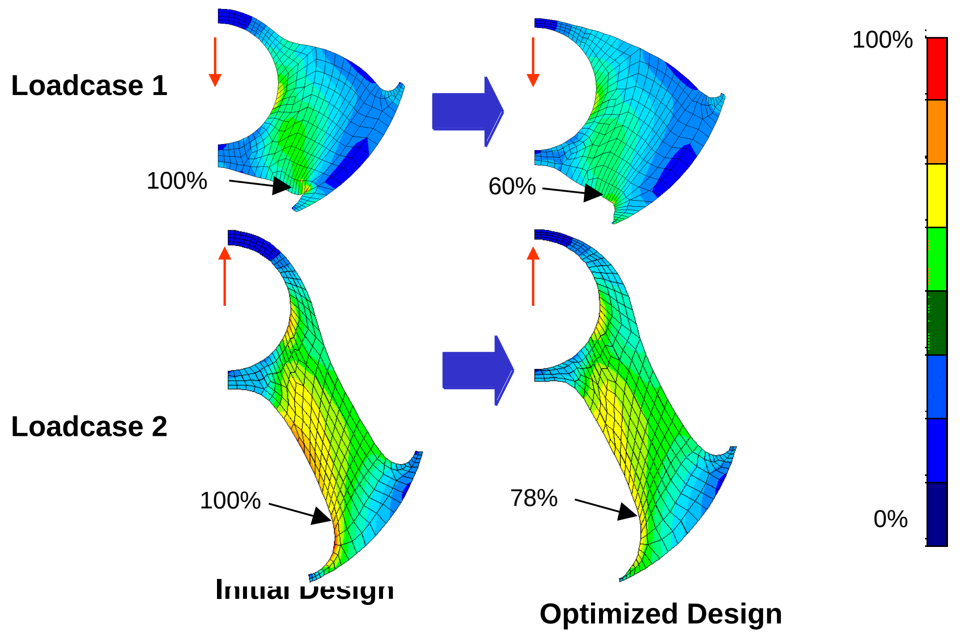


Fig. 5: Stress Distribution of the Initial and Optimised Design, v. Mises Stresses

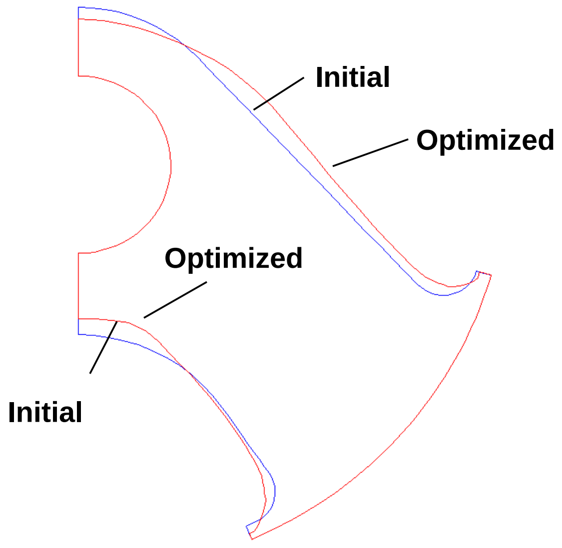


Fig. 6: Geometry Comparison of Initial and Optimized Design

3.2 3D-Optimisation of a Rubber-Metal Component

3.2.1 Model and Boundary Condition

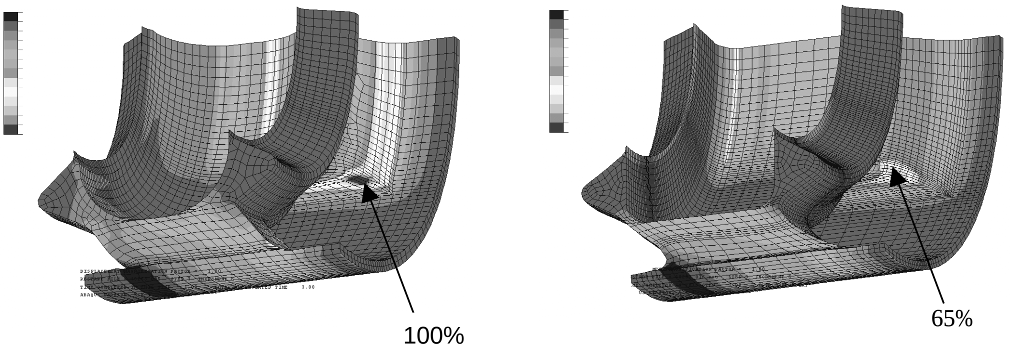
shows a rubber and metal component which is an example for 3D automatic shape optimisation with MSC/Construct-Shape. The rubber and metal bearing doesn't have a rotationally symmetric geometry because the holes aren't symmetric.

The cross-section of the optimized model has to be the same over all the model. The border of the holes has to stay perpendicular.

First, relevant boundary conditions regarding the component optimisation and shape optimisation must be identified. In this case the axial load is critical (dark spot in Fig. 7, left side).

3.2.2 Optimisation Results

The results of the nonlinear control calculation of the design optimized with MSC/CONSTRUCT has a more homogeneous stress distribution along the component surface. Therefore the elastomer material is used in a better way and as a result the stress level could be reduced for 35 %.



Initial Design

Optimized Design

Fig. 7: Stress Comparison of Initial and Optimized Design

Fig. 8 compares the different geometries of initial and optimized design. The changes in both cross-sections of the component are very small, but with this change of the geometry the effect on the maximum stress level is very high.

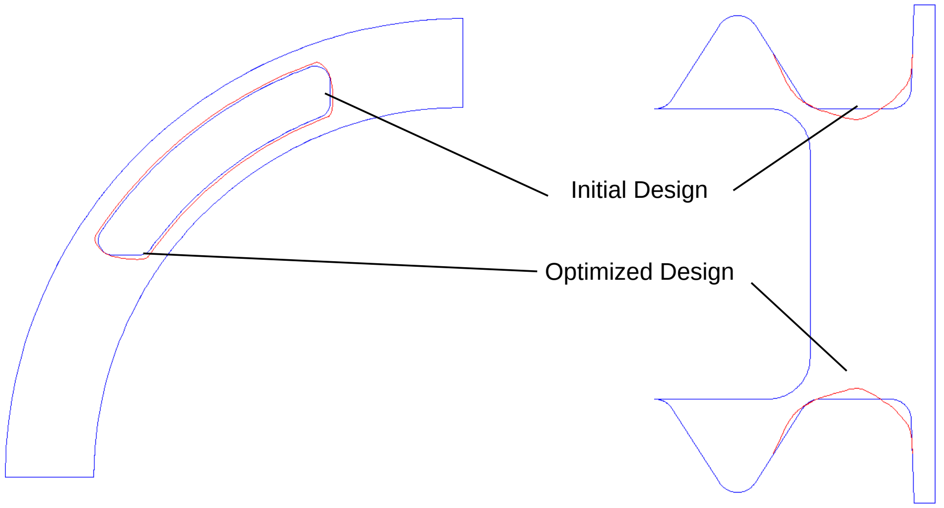


Fig. 8: Geometry Comparison of Initial and Optimised Design

3.3 Result Conclusions

The results may show that with a manual geometry change it would be very difficult to achieve such a high stress reduction. The feedback of the design engineers was that they wouldn't have thought in a solution like that. So to achieve a result like that would only have been possible with calculation of many different geometries which would have required high time and cost effort.

The use of automatic shape optimisation results in very time and cost efficient generation of better designs.

4. Procedure Discussion

MSC/CONSTRUCT Shape meets to a great extent the demands of the calculation department of our Freudenberg Research and Development Services.

Besides the robust optimisation algorithm and the easy use of the system, it is very advantegeous that there is no need to define parameters as design variables. Normally it is not possible in the design phase to predict whether a component has to be optimized or not. But for parametric optimisation already before doing the first calculation it has to be decided how to define the parameters. The parameter definition in many cases requires a high time and cost effort. If afterwards there is no need to optimize the already parametrized component the cost and time for building up a parametrized model is lost.

The efficiency in achieving better designs is even for experienced calculation engineers far better as using parametric optimisation. For that reason there's less time necessary for modelling many variants of a component. This time can be spent in the development of new calculation methods.

The linearized optimisation concept allows it to handle various nonlinear optimisation problems. Using this method, one has to consider that the stress distribution of the linearized model has to be similar to the nonlinear calculation. If it's not possible to find a load combination to reach this, it's necessary to have the possibility to optimize the nonlinear problem set, at least with material and geometric nonlinearities. It would be nice to have the opportunity to optimize contact problems, but at the moment with MSC/CONSTRUCT this is not possible as far as we think.

Because of the limits of MSC/NASTRAN for nonlinear problem sets (no user defined hyperelastic materials, convergence, definition of contact ...) at the moment the user in many cases has to look for substitute models to handle the great varity of hyperelastic problem sets.

5. Résumé

As shown in the paper, the customers requests of faster and more reliable development processes based on a wide calculation and simulation know-how can be satisfied using the shown optimisation strategies. There exist methods and programs for industrial use for shape optimisation purposes of mechanical loaded structures. A significant increase of the life span can be reached using those strategies. The need of more CPU time and time effort in the concept phase is already nowadays compensated by the advantage in the following working cycles in the product development phase. The nonparametric shape optimisation based on optimum criteria can be used very efficient for the optimisation of elastomer components.

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