Automatic Structural Optimization of Engine Components in an early Phase of the Design Cycle by using ABAQUS & TOSCA

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Abstract

Demands for state-of-the-art product developments are stronger than ever. Nowadays all industries are subject to accelerating changes in production and development and increasing aggressive competition. Complex demands can be fulfilled by applying simulation (ABAQUS) and optimization technologies (TOSCA) in an early phase of the virtual product development process. Product cycles have to become shorter by an increasing product complexity.

The ultimate challenges today are to become "faster – better – lighter – safer – cheaper" in order to:

- get the ability to make early decision in the design cycle
- reduce design and manufacturing cost
- reduce trial and error procedure in design
- reduce cost of materials
- increase engineering productivity

This paper will describe the usage of automatic structural optimization methods within an early design phase of the development process for modern combustion engines used by FEV. As an example for HFC (*high-cycle-fatigue*) failure the cylinder head will be used. The TMF (*thermo-mechanical-fatigue*) failure will be described based on an exhaust manifold, a very critical part in moder high loaded GDI engines.

1. Introduction

Modern combustion methods and the constant wish for an increase in the specific performance result in high thermal and mechanical loads on modern combustion engines. In addition, defined objectives for the engine weight are reduced, so that the vehicle weight, despite of increasing comfort and safety requirements, is not considerably increased. In order to shorten the development time, an interactive, simultaneous execution of design (CAD) and calculation activities (CAE), figure 1, is necessary. Here the product must be looked at in detail and be optimised in various disciplines and in a harmonized way of procedure to the development progress. In the initial, proactive phase the efficiency of virtual CAE-methods is high and quickly decreases in the second half of the development, which shows strongly reactive features.

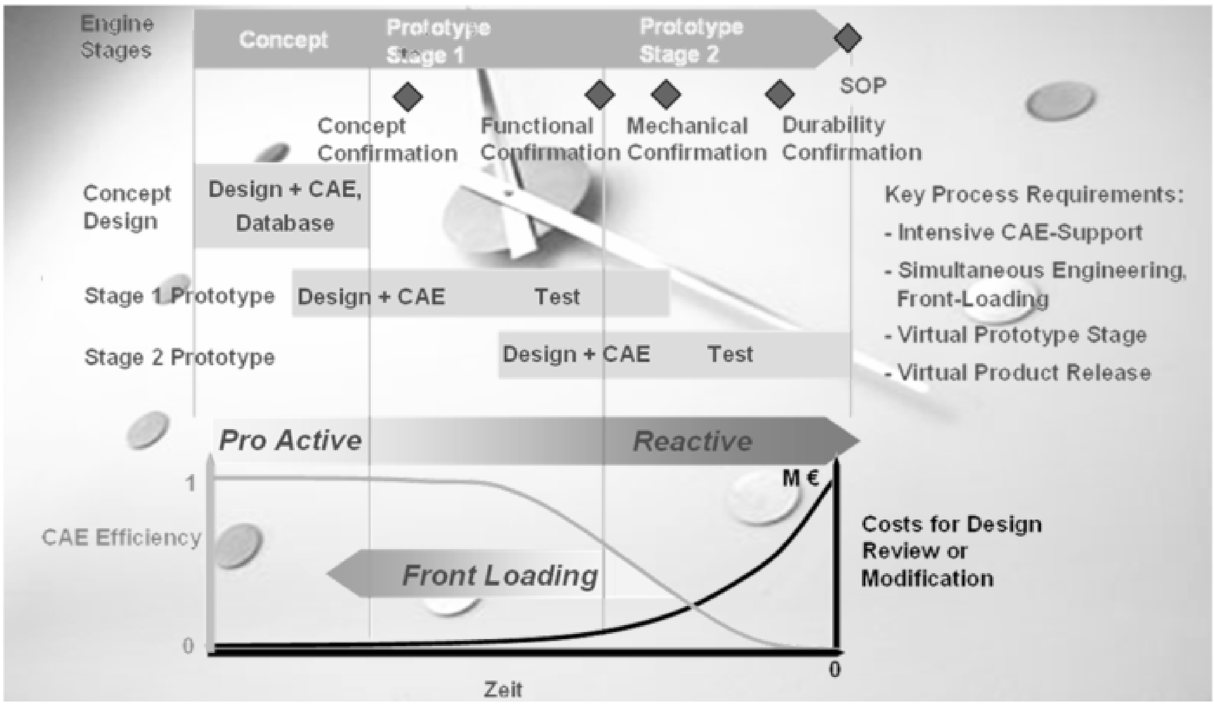

Fig. 1 Simultaneous CAE in the development plan

Corrections in the final phase are connected with high development and alteration costs. The initially mentioned consistent CAE-use therefore means the use of CAE-methods at an early stage and of the high information content gained from this, the so-called front loading. In CAE the use of program controlled structural optimisation is expected to further shorten the development process.

2. Shape Optimization

At highly loaded components with already very clearly defined basic shape, an exactly defined functionality and low variation possibilities, the shape optimisation has turned out to be a very productive assistant in detail improvement.
Shape optimisation means the modification of the surface of a component, in order to modify a certain target function, e.g. the maximum von Mises equivalent stress, or to modify a selected internal frequency in the desired way. In contrast to the topology optimisation no fundamentally new component form is determined.

Shape optimisation can be differentiated in parametric and parameter-free methods. At a parametric optimisation design parameters e.g. distances and radii are modified. In the ideal case this already takes place in the CAD-system with automatic secondary FEM (finite element method) calculation; in practice this method is often impeded by interface problems. Apart from that the space of the possible solution, owing to the limited number of design variables, is considerably restricted, due to which the solution found, in comparison to the possible solution, as a rule in the complete solution space only shows sub-optimal properties. At highly stressed components e.g. curvature resistant surfaces have turned out to be of advantage as regards stress distribution. By a simple parameterisation with radii curvature resistance can only be achieved with difficulty.

At parameter-free shape optimisation the part of the surface, which can be modified by the optimisation, is defined by, for example, a group of surface nodes of the FE-model. In the optimisation the selected nodes are moved in normal position to the surface, in which moving and smoothing of the internal mesh guarantees a correct FE-analysis. Therefore, each of these surface nodes represents a design variable. In connection with optimisation algorithms on the basis of optimality criteria a performance is achieved, which is independent of the number of design variables, owing to which a sufficient improvement at most of the models is achieved after 5-10 FE-analyses. Here, however, only target functions may be used, for which optimality criteria exist. These contain various comparative stresses, stiffness and natural frequencies, owing to which most of the application cases can be solved. As all selected surface nodes can be freely modified, the complete solution space is available for the optimisation. The result is a free shape surface, which is described via the surface mesh with the modified design nodes. This surface mesh is read into the CAD-system by means of suitable export formats and can there be converted into a CAD-model by reconstruction.

3. HCF (*High-Cycle-Fatigue*) Failure Analysis and Optimization for Global and Sub-Model

As an example the use of shape optimisation at the cylinder head analysis is dealt with. The thermal and mechanical analysis is carried out with the FE-program ABAQUS. The program FEMFAT is used for the determination of the operating safety. For shape optimisation the program TOSCA is used, which by starting the above mentioned programmes automatically in each optimization step carries out the complete analysis cycle of thermal, mechanical analysis and fatigue strength analysis and by means of the analysis results provides a modified geometry.

In particular the pre-tensioning forces of the cylinder head bolts and the pulsating gas forces exert mechanical stresses on the cylinder head, which at the same time is also subject to very high thermal loads. During manufacturing, assembly and engine operation the component is subject to further stresses. The stresses may be summarized as follows:

- Residual stresses as a result of casting process, thermal treatment and metal-cutting
- Pre-stresses through press fits of mounting parts, e.g. valve inserts and valve guides
- Pre-stresses through tightening of cylinder head bolts, injector and glow plug
- Thermo-mechanical stresses through different coefficients of thermal expansion of cylinder head and cylinder crankcase as well as other add-on or mounting parts and the material of the cylinder head
- Thermo-mechanical stresses through temperature gradients in the material of the ZK
- Mechanical stresses through the admission of dynamic cylinder pressure onto the flame deck

With the thermal analysis a temperature field for the mechanical analysis is determined based on boundary conditions of process simulation or from data-bases. Here a full load operating point is looked at. An overview of the input data used is given in the following list:

- Block/head → cooling fluent by taking the non-linear temperature dependency of the heat transfer coefficients for nucleate boiling into ac-count
- Operating gas → Cylinder wall and flame deck
- Operating gas → via piston to cylinder wall (piston heat flow)
- Heat through piston ring friction/Piston skirt friction
- Intake air → Intake port
- Exhaust gas → Outlet port
- Operating gas/valve → Valve seat rings
- Block/head → Engine oil
- Temperature dependent thermal conductivity of the individual components

The high-cycle-fatigue failure mechanism is caused through constantly critical combinations of mean and amplitude stresses. Here the local stress gradients, the orientation of stresses (tensile/compressive) and various material-specific parameters (surface, porosity, etc.) are of great importance. The lower stress limit of the alternating load is mainly produced by the load from residual stresses (casting processes, heat treatment, machining), assembly (bolting loads and press fits) and temperature (combustion); for the maximum stress the high-frequency periodic load, due to gas pressure, is superimposed. By the superimposition of residual stresses and cyclic loads, the fatigue life of the component may be considerably reduced. Critical areas of modern cylinder heads are typically the transition radii of the ports (intake/outlet) to the flame deck or oil deck, where erratic differences in stiffness are often found in the structure. For the following investigations the internal stresses were neglected. The implementation of the fatigue analysis in the optimization loop offers essential ad-vantages, as at complex structures places of highest mean stress are not always the places of greatest damage.

In order to be able to carry out automated structural optimizations on the basis of service life data, the simulation of fatigue strength must be integrated into the optimization process. In addition a suitable surface and corresponding modifications in controlling the optimization, a correct reaction of the optimization algorithm to the new input quantity must be guaranteed. For that an inverse transformation of the fatigue strength result into the tension space was carried out, i.e. a comparative stress correlated with the damage was calculated. By this way of procedure a stable and convergent optimization process was achieved. At the application described a fatigue strength calculation is started in each optimization loop after the thermal and static FE-solver-run (see figure 2). As input quantity the comparative stress correlated to the damage is entered into the optimization program, which correspondingly modifies the structure.

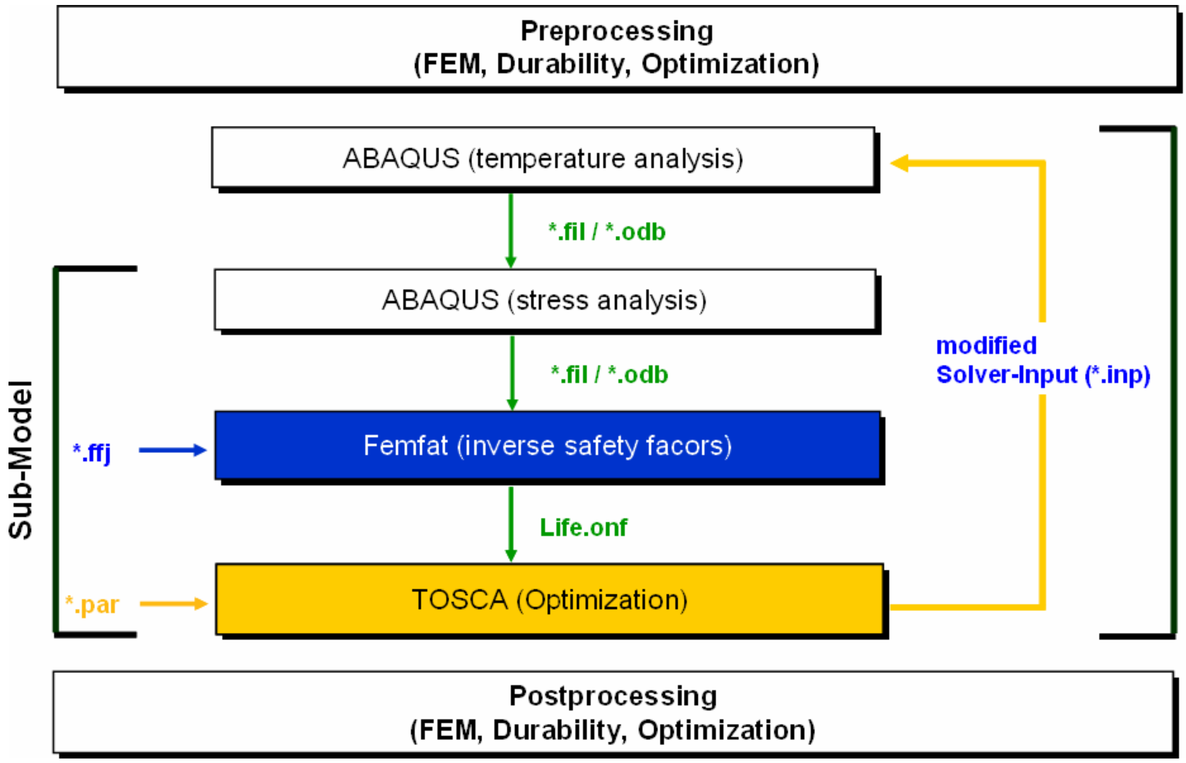

Fig. 2 Course of the optimization loop

In the analysis two basic ways of procedure were looked at and compared with each other. Time intensive, but also more exact, is the "closed loop" analysis, in which the global model is analyzed in each optimization step, owing to which also the response of the modified structure to the thermal analysis is taken into consideration. The basic way of procedure has already been de-scribed. As the analysis time needed for thermal and mechanical analyses is dominant in the analysis cycle, a reduced model consisting of one full and two half cylinders was selected (see figure 3).

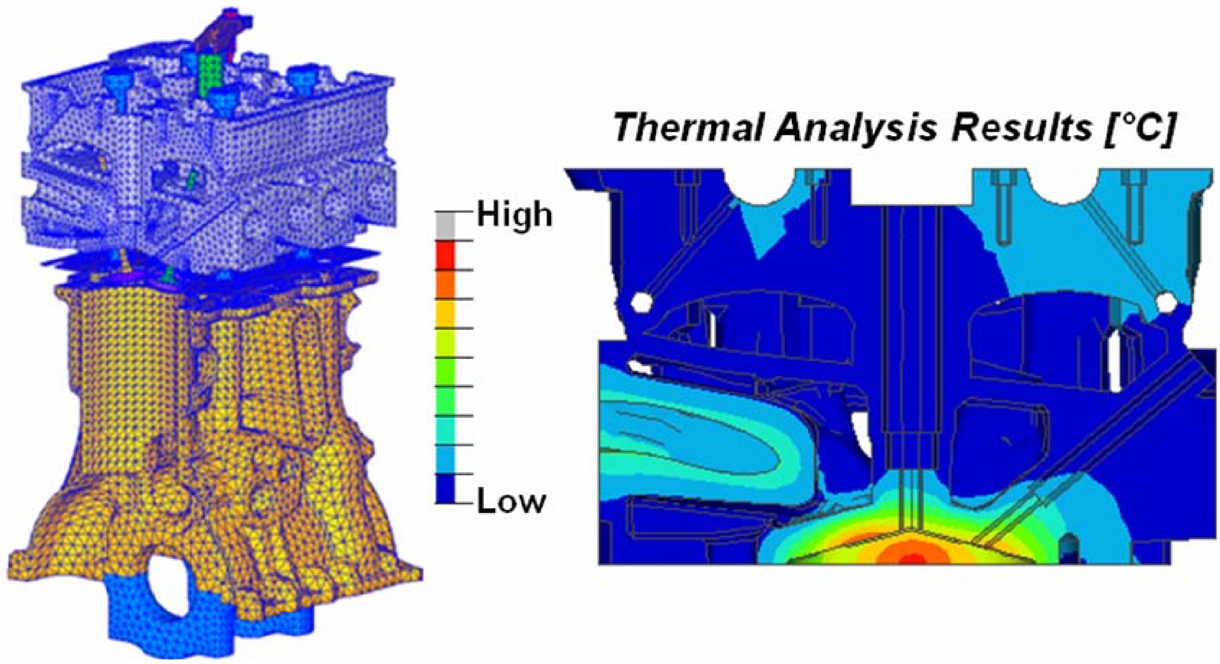

Fig. 3 FE-model with temperature distribution

The central waterside flame deck was released as design area. The mechanical analysis passes through the following load history:

1. Press fits
2. Applying the bolt loads
3. Thermal load
4. Gas pressure inner cylinder
5. Gas pressure outer cylinder

The two load cases are the relevancies for the fatigue strength analysis. Between intake and outlet ports areas of low safety are resulting, driven by mean stresses at moderate amplitude stresses (see figure 4).

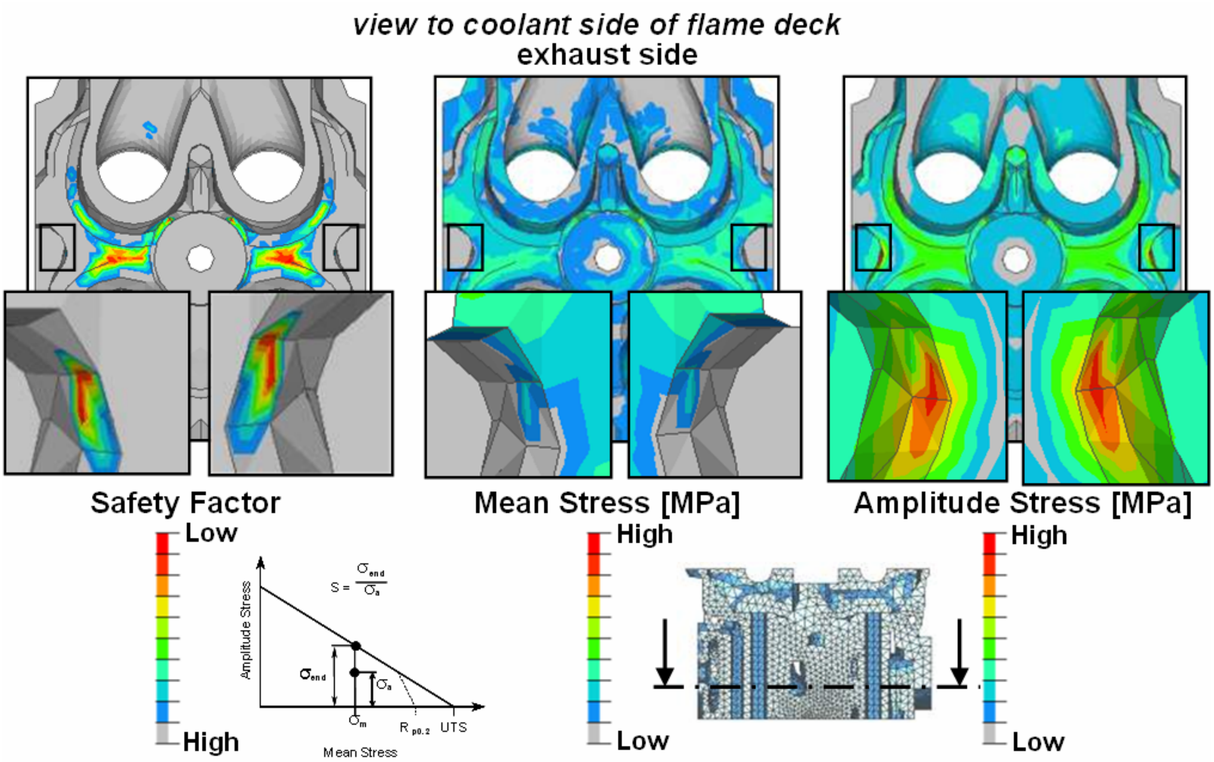

Fig. 4 Results HCF-analysis base model

An optimization loop takes approx. 7.5 h. As already mentioned, most of the time is used for the thermal and mechanical analysis. The optimization itself takes only a few minutes. In order to reduce the total time used for the optimization, the ABAQUS calculation model should at first be optimized as regards the calculation time. The operating safety in the critical range could be improved by 15 % (see figure 5).

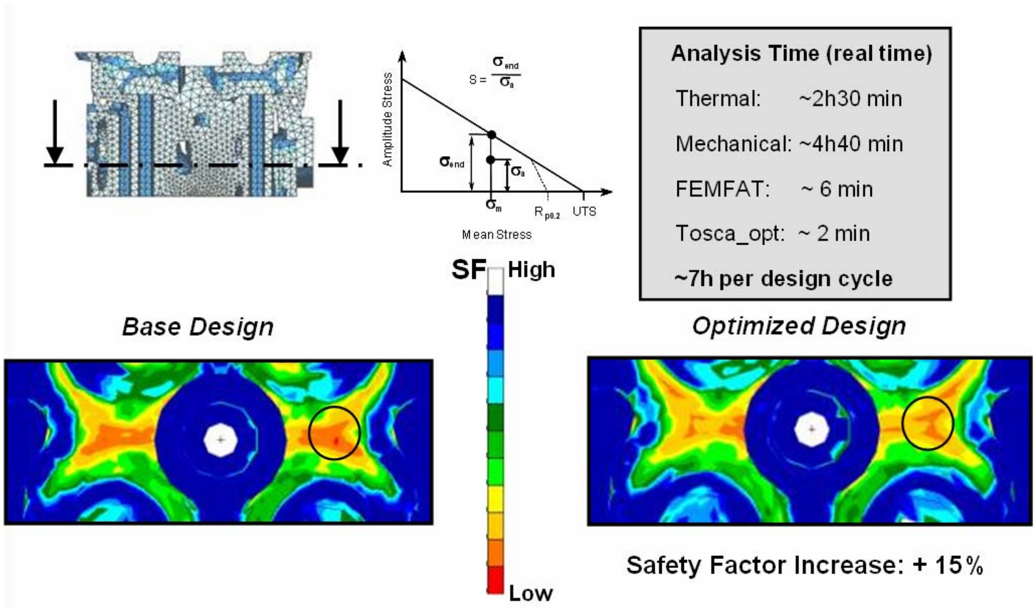

Fig. 5 Comparison HCF-results of base and optimized structure

Besides the long analysis time a further disadvantage of the optimization at the global model is the coarser discretization of the model resulting from shorter analysis times strived for. Owing to that the modification of the mesh during the optimization may earlier come to a critical element quality. The main advantage lies in the consideration of further influencing variables by the upstream thermal analysis. Compared to the classical optimization significant time can be saved.

The second method is based on the sub-model technique. As here only part of the global model is looked at, no feedback to the temperature can be given. Apart from that the modified model structure may not significantly influence the stiffness of the global model, as otherwise the method itself is not truly applicable and the results are falsified. Regarding the analysis time there are, however, clear advantages. Although the model has been improved in the critical range, an iterative loop takes longer than 1 hour. Consequently, the optimization can take place over night and owing to the finer model resolution better element qualities are achieved during the optimization. Here too the critical range could be improved by 14 % (see figure 6).

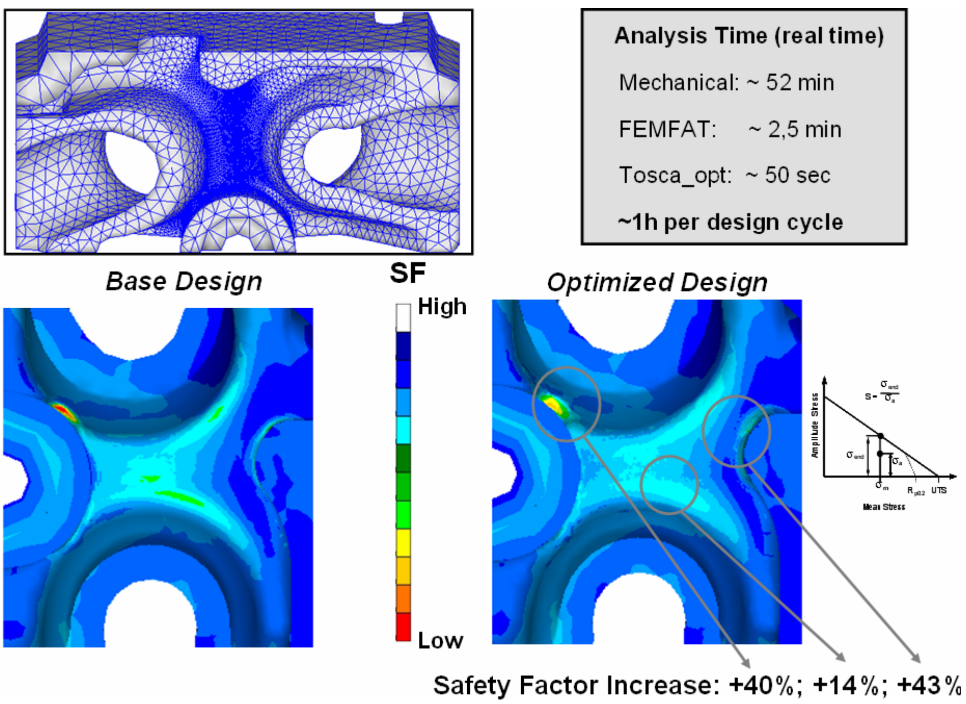

Fig. 6 Comparison HCF-results base and optimized structure at the sub-model

Furthermore, also stress concentrations could be improved in areas, which in the global model were not sufficiently recognizable. Here, the grade of optimization is up to 40 %. Therefore, the optimization at the sub-model is especially useful for the achievement of first quick results and optimization of local stress concentrations. In order to determine the influence on global stiffness and temperature, the results must be verified at the global model.

4. TMF (*Thermo-Mechanical-Fatigue*) Failure Analysis and Optimization

Apart from the cylinder head structure the shape optimization is also applicable at all further highly loaded structures at the combustion engine. A further example is the exhaust manifold. At this component the damage is not caused by alternating ignition pressures, but by thermal load alternations.

Already after the first load cycle's plastic deformations can often be seen in some areas of the exhaust manifold. The high material temperatures in connection with the limited possibility of thermal expansion, owing to different material parameters and the screwed connection, lead to high compressive stresses, which locally exceed the yield point of the in hot condition less solid material. In these plasticized zones the compressive stresses, after cooling down of the engine, change into local tensile stresses, which in the unfavorable case can now locally exceed the tensile yield point. In this case cyclically repeated plastic strain amplitude occurs, which is the basis for the thermo-mechanical failure mechanism. Of special importance in this connection are also the contact formulations between cylinder head, gasket and exhaust manifold, as well as the non-linear behavior of the exhaust manifold gasket. Compared to the fatigue life characteristics from experiments, the service life of the component can be determined via strain or energy approaches.

As the optimality criteria also apply to moderately non-linear analyses e.g. plasticity or hyper-elasticity, also certain non-linear analyses can be used in shape optimization. As regards plasticity, for example, a homogenization of the elastic and plastic stain energy is strived for, by which the maximum strain energy and with that also the maximum plastic strain is reduced. Therefore, the optimization quantity in this example, in the first formulation, is not a damage that is looked at, but plastic strain amplitude. From the results of test bench runs a good correlation of crack starting points to areas of a high plastic strain amplitude can be derived in comparison to analyses (see figure 7). An extension for a TMF-based damage calculation and integration into the optimization process is, however, in principle possible.

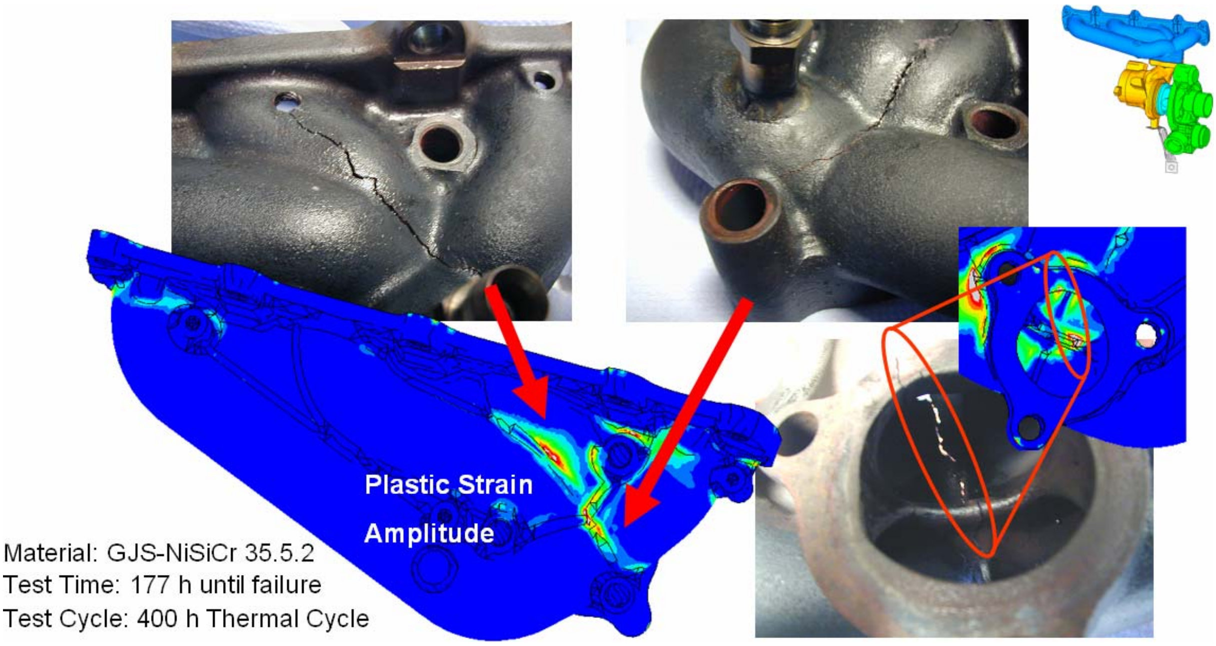

Fig. 7 Comparison simulation and hardware at an early design stage

The determination of the damage through TMF is comparable to the already described analyses at the cylinder head. At the thermal analysis also radiation influence, besides comparable boundary conditions as used for the cylinder head analysis, are taken into consideration. Averaged heat transfer coefficients and gas temperatures are determined in instationary CFD-analyses. The mechanical loads consist of the following:

- Pre-stresses from bolt loads
- Thermo-mechanical stresses caused by various thermal expansion coefficients of cylinder head and exhaust manifold as well as other mounting parts.
- Thermo-mechanic stresses through temperature gradients in the materials of the component parts.

Residual stresses and dynamic stresses can be neglected for the determination of the TMF-failure.

At the optimization of the exhaust manifold the analysis takes place according to the „closed loop" method, i.e. by integration of the thermal analysis. The gas-side boundary conditions are kept constant, as in the first approximation the local modifications at the geometry do not have any significant effects on the gas flow. As an exact representation of the temperature distribution for the evaluation of TMF is of special importance, measurement based on thermo-scan methods or by means of thermo-color can be carried out in the preliminary stages of the analyses (see figure 8).

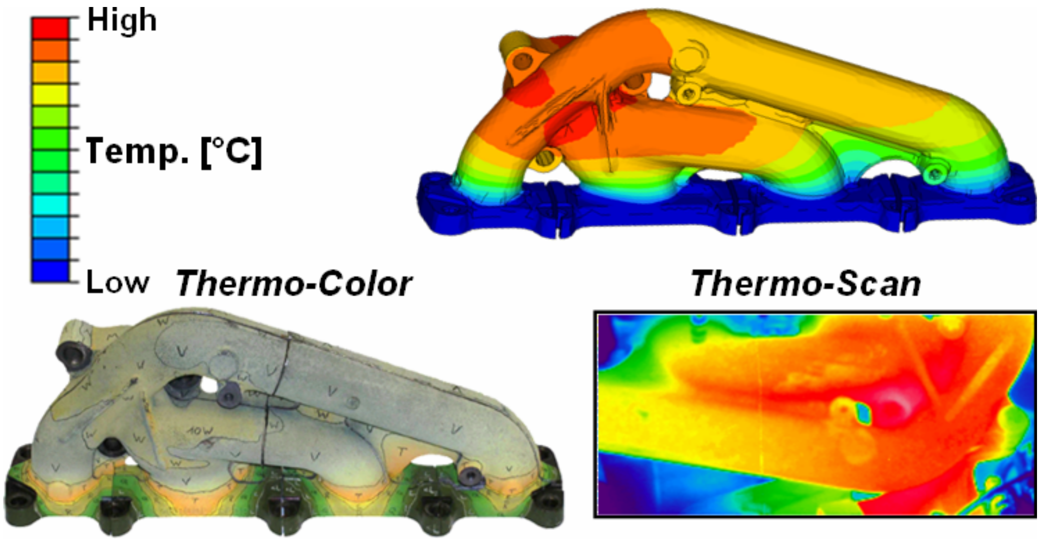

Fig. 8 Temperature distribution from simulation and measurement

As design area all internal and external surfaces of the ports were selected. The geometry of the flange surfaces and bolt bores were fixed. During the mechanical analysis the following load history is passed through:

1. Assembly
2. Thermal load
3. Cooling down to room temperature
4. Thermal load
5. Cooling down to room temperature

The total analysis time is at approx. 2.5 hours, with the thermal and mechanical analysis representing almost 100 % of the work. In total 30 optimization loops were carried out. The release of such a large design area is a challenge for the optimization algorithm. Local modifications at one area can change the total stiffness of the exhaust manifold and consequently influence the results of further areas. This is very well recognized in the internal area of the flange to the turbocharger. Here after 9 cycles a plastic strain reduced by 53 % is achieved. After 13 cycles the local result aggravates to –35 % and the optimal result is achieved after 15 cycles (see figure 9).

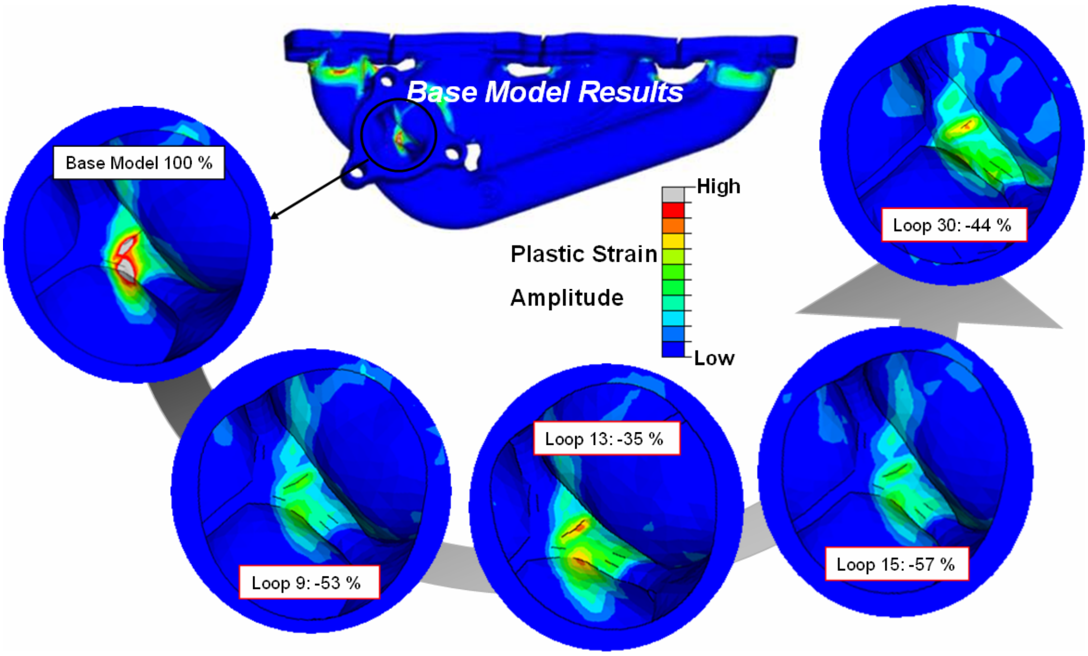

Fig. 9 Optimization results via cycles

It must be taken into account that the basis is the result of a classic optimization carried out over a period of several weeks. A reduction in the plastic strain by more than 50 % within 75 hours in this case represents an essential time saving in the development process. Finally, it should be investigated for the various areas, which cycle (geometry stage) delivers the optimal result and from that the best combination of all areas should be selected. This geometry should be verified in a final analysis. A feedback to the flow analysis would be of advantage. Figure 10 shows the comparison between the basic geometry and the optimization result after 30 cycles. It can be easily seen that the ribs on the upper side of the exhaust manifold almost receded. These had been applied before during the „classic" optimization. Essentially improved appears also the optimized structure between the flange facings. Through the limitation of the design area to critical areas the number of necessary optimization loops can be reduced.

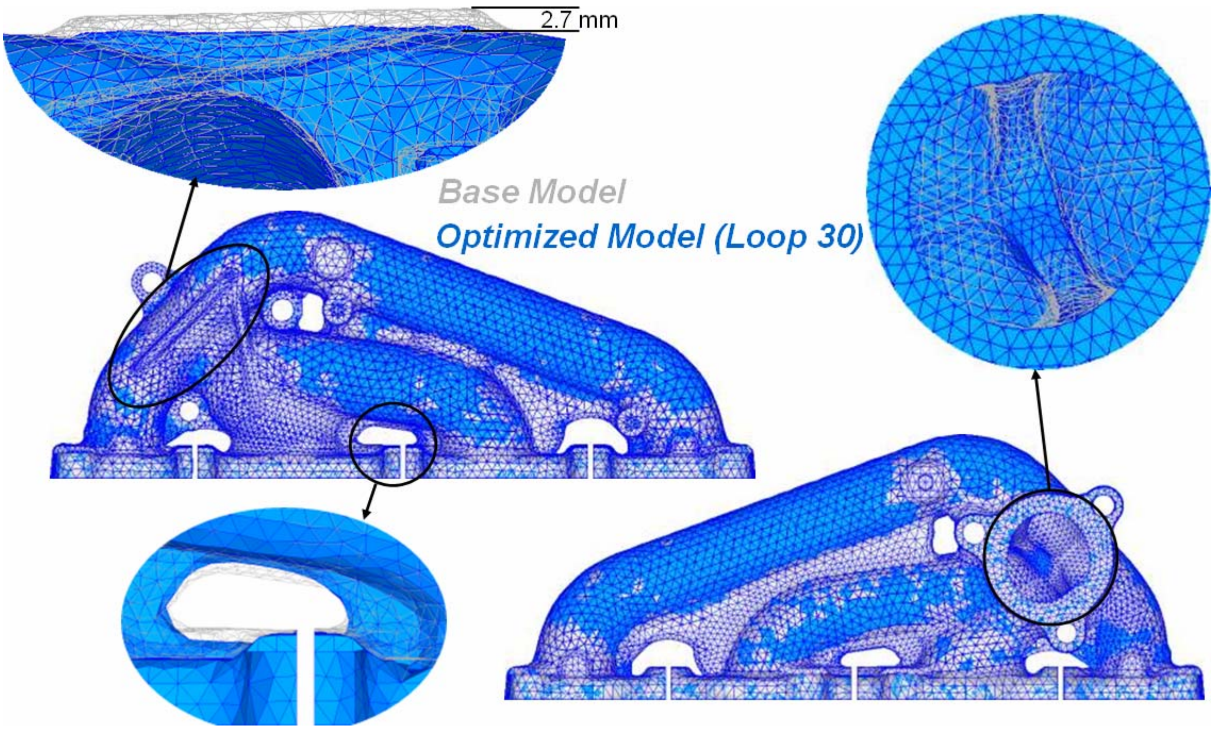

Fig. 10 Comparison basis and optimized geometry

5. Conclusion

The possibility of carrying out a shape optimization with TOSCA on an already existing FE-model, by taking non-linear behavior and specific service life simulation into consideration, has turned to be an enormous relief and notice-able improvement in the development process. The geometry modifications achieved that way are partly only very minor, have, however, a very strong influence on the service life and with that on the quality of the component parts. Owing to that, on the one hand, material saving at equal service life or, on the other hand, at using the same materials, a significant extension in the fatigue life can be achieved. Also the complex task of the optimization of a large area concerning plastic strain amplitudes delivered very good results with a reduction in the critical values of 50 % and more. Currently FEV finished the first steps for the implementation of the FEV Software LowFat into the optimization cycle for TMF driven problems.

In the traditional modification process on the basis of CAD-variant constructions and their verification by means of FEM the same improvement potential can only be achieved with much higher expense, as the current “classic” optimizations could, in the best case, be carried out in diurnal rhythm. The exhaust manifold shows the potential of reducing the time needed for the optimization from weeks to days.