Designing Exhaust Manifolds Using Integral Engineering Solutions

ABSTRACT

Exhaust manifold cracks from Thermomechanical Fatigue (TMF) are often seen on highly loaded engines, due to increasing marketplace demands for performance and emissions. A constant search for higher strength materials is needed, due to maximum gas temperatures that in some instances are already above 1000°C. The use of virtual prototypes for creating a development strategy for testing will reduce expense and time as opposed to using physical prototypes. The design and analyses engineers are assisted through advanced simulation technologies, which help locate critical areas during the early phases of development so that local structural weaknesses can be removed. A variety of studies have been published over the last few decades regarding the identification of these critical areas, which include considering kinematic and isotropic hardening, creep in material modeling and consideration of plasticity, creep and oxidation in lifetime modeling.

This study focuses on the development of a reliable approach to predict failure of exhaust manifolds and on the removal of structural weaknesses through the optimization of design. The failure modes for TMF cracks, vibration and exhaust manifold gaskets are emphasized. The resulting optimization used both manual and automatic methodologies, which highlight the correlated advantages and disadvantages of the proposed design. Examples of the applications show that automatic shape optimization is a powerful tool in the development of exhaust manifolds, which face ever decreasing development time. Engineering expertise is still needed required to fully utilize this technique, because the results strongly depend on defining the problem. The optimization of cast and fabricated manifolds (single or dual wall design) requires different techniques, due to the production restrictions. The locations where failures occur, on both the exhaust manifolds (cast or fabricated) and exhaust manifold gaskets, are predicted with high degree of accuracy. This study also shows an optimization package, which provides practical solutions to engineering problems through the removal of local structural weaknesses on highly loaded exhaust manifolds.

INTRODUCTION

TMF cracking on exhaust manifolds is an issue that engine manufacturers have been facing more frequently over the last decade. The primary reason for the TMF cracking is the significantly increasing gas temperatures. Those temperatures have increase because of market demands for high specific power and regulations requiring low emissions. The increasing gas temperature is equated to three main failure mechanisms within the exhaust manifolds:

- Oxidation (environmental effects)
- Creep (time effects)
- Mechanical fatigue (cyclic plasticity)

Each of these failure mechanism's contributions to the overall damage is a function of design, material and loading:

$D_{overall} = \sum D_i$ (design, material, loading), where i = oxidation, creep, plasticity

Oxidation issues are typically resolved through the use of materials which have a higher oxidation resistance. However, since oxidation is primarily dependant on temperature, practical solutions with local design modifications (material, loading = constant) are very difficult. Additional difficulties lie in assessing the oxidation damage, specifically where a solid background is missing. Studies have been completed, which provide an oxidation damage prediction model with a phasing factor that has showed good correlations for 1070 steel [1]. However, to identify the model parameters, a large number of material tests are required and it is doubtful that the model would be valid for other materials. Typically, the material used has a variety of trade-offs for high temperature strength and oxidation resistance. The primary goal in material selection is not to reach the abnormal oxidization zone [2] under operating conditions.

Current documentation is not consistent with regards to the extent of creep damage in exhaust manifold applications. Some studies cite the plastic strain range as the dominant factor for the damage [3-6]. However, other authors define creep deformation as the primary influence on total damage [7] or consider viscous strain either explicitly or implicitly in lifetime evaluation [8-9]. Testing of the exhaust manifold thermal cycle includes dwell time under both full load and motoring conditions. Operating the engine under full load conditions (maximum temperature), subject the exhaust manifold to compressive loads (out-of phase loading). Under these circumstances, creep damage is considered a secondary effect. However, the quantity of local relaxation and its impact on predicting the lifetime of the manifolds must take into consideration the explicit key factors of creep strain/damage or implicit considerations of using mean/maximum stress dependency.

The main cause of exhaust manifold cracks is defined by many authors as plasticity, which can be strongly influenced through changes to the local design. Replacing the material can be one solution. However, the task of engineering is to locate a cost-effective material, which exploits its strength under predefined loading conditions. The prerequisites for cost-effective solutions are a reliable failure prediction approach and an intelligent plan for optimization.

Recently, a number of TMF life prediction methodologies for exhaust manifolds have been developed. A variety of different equations and damage models for predicting the manifold's lifetime have both shown a good correlation with results of the experiments, especially for the crack locations. Mathematical models for material and lifetime prediction are combined with material parameters to provide that basis for these approaches. Consequently, it becomes difficult to change to another method when an approach is selected and the material parameters are accumulated in a database through testing. In order to provide an intelligent solution, which can help engine manufacturers to solve their problems, the developers need to have an optimized approach. This study is unique in that it provides an optimization methodology for developing failure-free products instead of simply an as-is state analysis.

EXHAUST MANIFOLD TYPES AND MATERIALS

Exhaust manifolds are classified as cast and fabricated. Cast manifolds can be designed as a separate part but can also be integrated in the cylinder head structure. Fabricated manifolds are known in single and dual wall design, where an interior and exterior sheet metal is separated by an isolating air gap.

Exhaust manifold design has to reflect the individual material characteristics and loading conditions by appropriate stiffness and low operating temperatures in addition to satisfying main drivers of engine development; namely emissions, power and fuel consumption. Table 1 summarizes the main types of exhaust manifolds with some example materials.

Lightweight design principles in order to reduce CO_2 emissions and fuel consumption with less friction losses is realized by downsizing concepts, where small and compact engines are built. Another trend is to place the catalyst as close as possible to the fabricated thin wall exhaust manifold to reach a quicker catalyst warm-up. Here, some trade-offs to mention are the high dynamic loading associated with the thin wall exhaust manifold – catalyst combination and the manufacturing / packaging constraints. Once the priorities are set and product requirement specifications are considered for decision making, the structural analyst has the material and design degrees of freedom (up to a certain extent) under predefined loading conditions to achieve target structural integrity.

Type	Materials	$T_{max}^{material}$ (°C)	Main Pros & Cons	Demands
Cast	GJS-SiMo-5.0-1.0 GJV-SiMo-4.5-0.6 GJSA-XNiSiCr 35-5-2 GX40CrNiSi25-20	700 - 830 800 - 860 850 -1050 1050 -1100	+ production costs + design flexibility - emissions - weight	Emissions, Power, Weight, Size, Production costs, Acoustics, Dynamic durability, Thermal life
Fabricated	X2 CrTiNb 18 X5 CrNi 18-10 X6 CrNiTi 18-10 X15 CrNiSi 20-12	900 - 950 800 - 850 850 - 920 950 -1000	+ emissions + thermal stability - dynamic loading - complex design	

Table 1: Exhaust Manifold Types & Materials versus Demands

In early design stages, when main parameters like mean exhaust gas temperature is known, a proper material choice is initially driven by benchmarking. Figure 1 shows a screenshot from FEV Engine database assisted by published data. From the structural point of view, an early crucial mistake (e.g., expected max. temperature exceeds material limits) such as wrong material selection can be eliminated while the information basis for analysis evaluation is implicitly constructed.

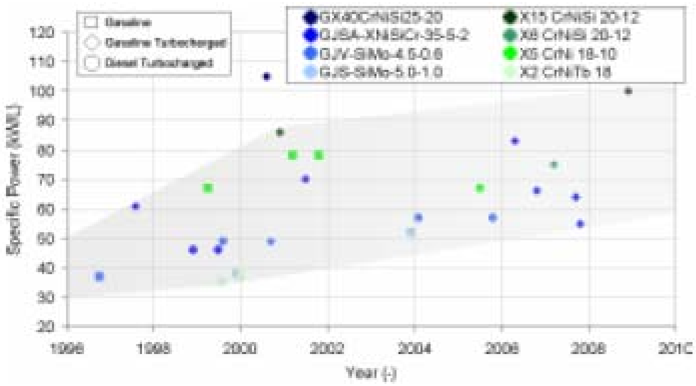

Figure 1: Exhaust Manifold Material Benchmark

Chemical composition and microstructure of the materials define the thermal strength, resistance to creep, oxidation and microstructural changes, which are of utmost importance for exhaust manifold applications. Higher strength materials are continuously searched for accompanying timely and costly testing programs. In [10], Si and Mo content of a SiMo ductile iron are raised to amplify thermal fatigue life and reduce creep effects.

LOADING AND MATERIAL MODELING

The local critical loading of any exhaust manifold can be explained with the following:

- Temperature level - defines the level of creep, oxidation and micro-structural changes (strength decrease)
- Thermomechanical restraining - local restraining due to the internal loads (temperature gradients) and external loads (bolting, gasket, thermal expansion coefficient difference) in combination with the structure geometry (stiffness distribution)

To highlight, the CAE engineer's task is to find the critical locations under defined boundary conditions (design, loading, material) and then to reduce temperature levels/gradients and/or relieve the mechanical strains. As for that, at first, material's stress-strain response under variable thermomechanical loading has to be predicted.

Material modeling and parameter identification procedure, which is implemented in FEV_ParFit software, is depicted in Figure 2. In the predevelopment stage, the process starts with a prediction of exhaust gas temperature and an approximation of peak expected material temperature accordingly. In case of non-availability of specimen test data, the test program is defined considering the expected peak material temperatures. Specimen test results are collected in a four-dimensional database where the experiment class (e.g., monotonic tension, relaxation, tmf, ...), experiment number, time (the independent variable, does not necessarily need to be time) and the response constitute the four dimensions.

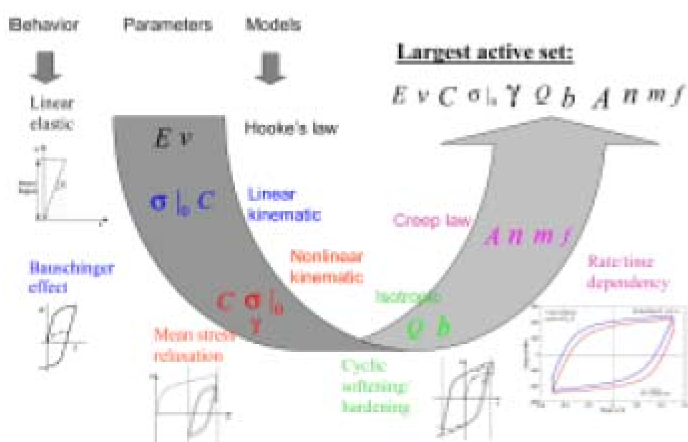

Figure 2: Material Parameter Identification

Post-processing on test results delivers the important information of observed material behavior. For the sake of simplicity, material parameters, which are responsible for the observed material response, are activated for the identification process. Alternatively, all parameters can be activated but in this case the identification time increases on one hand and the calculation time may require hundreds of cycles, which could be infeasible in an engine development timeframe.

Next step is a general optimization process where gradient-based, stochastic-based, Kalman filter and neural network methods are used to minimize a defined error function. Gradient-based methods in combination with constraint definitions for material parameters provide fast and reliable solutions. FEV_ParFit uses two gradient-based algorithms:

- A combination of Quasi-Newton and Gauss-Newton when no constraints are defined
- Sequential Quadratic Programming based on a Quasi-Newton update when constraints are defined

TMF LIFETIME PREDICTION

Many lifetime prediction approaches have been published over years [12-16] (See Table 2). TMF life assessment approaches could be classified as strain-based, energy based, damage parameters, fracture mechanics, cumulative and micro-structural approaches. Independent of the theory used, the life prediction is based on functions of the induced strains and stresses due to thermomechanical loading and the material parameters.

Manson Coffin:	$\varepsilon_{pl,amp}$	=	$\varepsilon_f' * (2N)^c$
Total Strain Approach:	$\varepsilon_{mech,amp}$	=	$\sigma_f'/E * (2N)^b + \varepsilon_f' * (2N)^c$
Morrow Equation:	$\varepsilon_{mech,amp}$	=	$(\sigma_f' - \sigma_m)/E * (2N)^b + \varepsilon_f' * (2N)^c$
SWT Parameter:	$\sigma_{max} * \varepsilon_{mech,amp} * E$	=	$(\sigma_f')^2 * (2N)^{2b} + \sigma_f' * \varepsilon_f' * E * (2N)^{b+c}$
Energetic Approach:	$\Delta W * N^\beta$	=	C

Table 2: TMF Life Prediction Approaches [12-16]

In [17], a good correlation of life span results for different types of cast irons was shown using a modified energetic approach, where the parameter C is defined as:

$$C = C_0 \cdot \varepsilon_f' \left(\frac{\sigma_f' - m\sigma_{mean}}{\sigma_{max}} \right)$$

The above stated modified relationship combines the uniaxial behavior of the experimental results and the multiaxial nature of the 3D exhaust manifold structure. This combination is dictated by the utilization of available uniaxial data and search for material response under multiaxial loading. Mean stress effects are incorporated explicitly by mean stress in the numerator and implicitly by maximum stress in the denominator. Because of this implicit connection, there is a nonlinear power relationship which reduces to an approximate linear dependency of logN on mean stress in the application range. For the case of completely reversed data, the number of cycles to failure depends both on dissipated energy and maximum stress, which is a result of norm calculations with the critical cutting plane approach.

Fatigue ductility and strength coefficients of materials under isothermal loading conditions can be found in the literature. In case there is no such data under anisothermal conditions, isothermal experiment results are utilized in the first validation loops. The material parameter ‘m’ stands for mean stress sensitivity and can be acquired from temperature and strain controlled experiments. The normalized slope (m) of mean stress vs. mean strain curve is in the range of 1…2.

Figure 3 depicts the correlation coefficients of different damage indicators given in Table 2 and the modified energetic approach parameter which can be stated as:

$$\Delta W_{mod} = \frac{\Delta W \times \sigma_{max}}{\sigma_f' - m\sigma_{mean}}$$

The modified energetic damage parameter approach is promising with its maximum correlation to measured lifetime. While for a precise prediction this information is invaluable, in order to optimize the design relative improvements are searched for and hence other indicators could also be utilized.

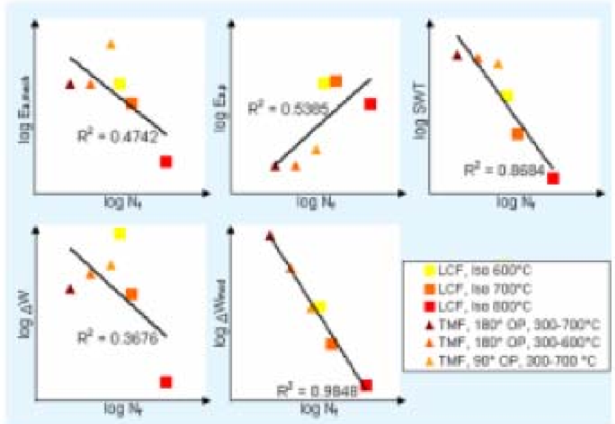

Figure 3: Correlation of Damage Indicators to High Temp. Isothermal and Thermomechanical Results of GJS-SiMo

BOUNDARY CONDITIONS AND ANALYSIS TECHNIQUES

THERMAL ANALYSIS - The temperature distribution is the most important boundary condition to drive the structural analysis. During an engine development process, different levels of thermal boundary conditions are used. In a very early stage of a development, only a rough initial geometry is available. In this stage a combustion process is being developed and might not be fixed. Analytical results are not available to educe differentiated boundary conditions for a thermal analysis.

Boundary conditions are initially derived based on benchmarking of similar designs and estimated gas peak temperatures. At a later point in time, the combustion process is simulated by 1D-analysis. This gives the opportunity to develop a more detailed set of boundary conditions for thermal analysis. Heat flux can be mapped more locally to the manifold. Based on the 1D analysis, mass flow, pressure and gas temperature are known over a complete crank cycle. This information is used to drive a detailed 3D CFD-analysis, which delivers local heat transfer coefficients and wall near gas temperatures as a mean value over one combustion cycle.

Special mapping programs developed by FEV are able to transfer CFD-results to FE boundary conditions between dissimilar meshes. The outputs are ready-to-use datasets, which could be directly used to drive the analysis. This is a very robust and cost effective solution compared to a conjugated heat transfer analysis, which is more time consuming.

Besides gas convection acting on the interior side of the exhaust manifold also exterior convection and radiation are decisive in temperature field; especially in areas where small gaps between manifold surface and adjacent parts are found (e.g. heat shields). For air gap isolated fabricated manifolds (dual wall), radiation between the inner and outer metal sheet needs to be considered.

Especially the exterior heat fluxes are varying dependent on the operating conditions one will find in test bench (convective heat flux due to fans) or in production applications. The availability of measurements gives the opportunity to adjust boundary conditions related to this local context. Measurements also allow introducing transient analysis techniques, where local temperature logging can be used to adjust boundary conditions in order to simulate a test bench environment (Figure 4).

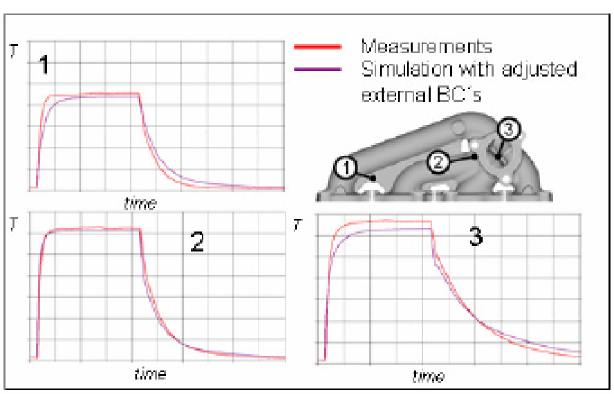

Figure 4: Transient Thermal Analysis Results

STRUCTURAL ANALYSIS - Main loads acting on the manifold structure are temperature field (interior load), bolt forces and dynamic excitation (exterior loads). Target of the structural analysis is a detailed evaluation of manifold stresses, strains and fatigue life, gasket pressure distribution and bolt force evolution – all regarding cyclic thermal loading.

In the first step of structural analysis, bolt forces are applied. The assembly of the exhaust manifold with bolts is torque driven in general, where the bolts are not tightened into yield. Based on bolt dimension, strength class information, thread pitch, friction coefficient on the mating surfaces and assembly torque (and its tolerances) an initial estimation of the bolt force variation can be calculated by use of the VDI guideline 2230.

It becomes obvious, that very small deviations in assembly pre-torque cause huge a variation in axial bolt force. In the case that bolt pretension is set to minimum, plastic straining in the exhaust manifold is usually lower than by use of maximum bolt pretension. Gasket sealing pressure might become lower in mean value, yet, can also be better distributed over the sealing area due to lower bending deformation of the flange. Both, minimum and maximum bolt forces are standard base analysis in order to quantify influences of change in bolt pretension.

During thermal cycling, in addition to inelastic deformations, also the evolution of bolt pretension is to be monitored. When the structure is heated up, axial and lateral deformations of the manifold cause the stresses in the bolt to increase. Once the yield limit of the bolt is exceeded, a noticeable pretension loss could be observed in cold state. Relevant parameters are thermal expansion coefficient and friction coefficients between contacting parts.

FAILURE MODES OF EXHAUST MANIFOLDS

Failures of exhaust manifolds are mainly caused by the extreme temperature amplitudes/gradients the part has to withstand. A secondary cause for failures is the dynamic excitation of the exhaust subsystem, especially if not negligible masses of attached parts like turbocharger or close-coupled-catalyst are driven into resonance. Typical structural failure modes are manifold cracking and leakage. Those are related to the design and boundary conditions if a proper material choice was done initially. Understanding the root cause of a failure is the most challenging part on the way to a solution.

UNDERSTANDING FAILURES

<u>TMF cracking</u> – An initial thermal loading of exhaust manifolds can cause the material to exceed the yield stress in large areas of the exhaust manifold. Cyclic temperature loading causes a few areas to exhibit local cyclic plastic straining of the material, which may cause a crack initiation. Depending on the location of the high loaded areas, individual design parameters need to be considered in order to find a target-oriented optimization strategy. It becomes obvious that a detailed knowledge of the system behavior is needed, in order to interpret results correctly.

From a simulation point of view the models used for analysis need to allow for a detailed review of individual parameters. The engineer needs to find a compromise between complexity of model and boundary conditions versus reliability. Specific design restraints for each engine create individual manifold solutions. Therefore, influencing parameters have to be reflected for each design in front of a system optimization. Simulation is here a very flexible instrument to quantify the influence of each parameter. Depending on the number of parameters, statistical DOE methods can be used to efficiently work out the main influencing parameters.

<u>Leakage</u> – Besides cracking of exhaust manifold systems, the leakage problem is very often also related to cyclic plastification of exhaust manifolds. This failure is very often found on the test bench with increasing number of test cycles. Once leakage occurs, a partial destruction of the gasket and the flange occurs, which may lead to an ensuing manifold crack due to a changed force flow in the exhaust manifold. Also here a detailed knowledge of the influencing parameters like bolt pretension, friction between adjacent parts and nonlinear gasket behavior is needed to get an initial understanding of the problem.

<u>High cycle fatigue</u> – High cycle fatigue (HCF) problems at the exhaust manifold are caused by dynamic excitation. This kind of problem is not discovered very often, and is mainly related to unfavorable bracket design. In a first step, an Eigen frequency analysis of the manifold subsystem gives an initial idea; if the system is excited in the first dominant engine orders (Figure 5). However, this gives only a first preview of the subsystem excitation and may be seen as an indication for further investigations, where a detailed dynamic analysis [18] overlaying the assembly, temperature and dynamic loading of the system is conducted to calculate the high cycle fatigue safety margin.

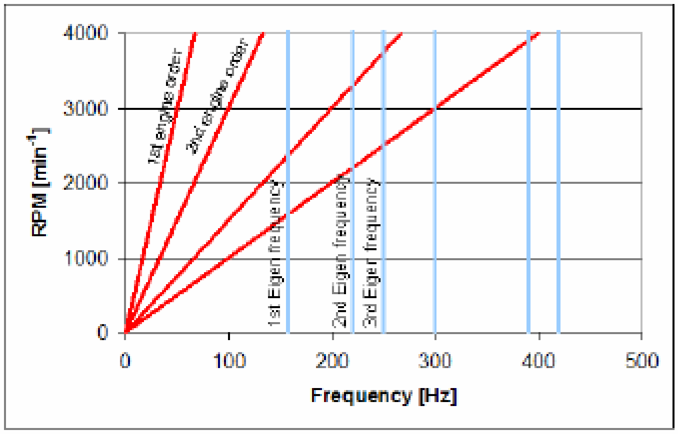

Figure 5: Engine Speed Over Eigen Frequency

OPTIMIZATION

OPTIMIZATION STRATEGY

Besides technical targets (functionality and reliability), which are mandatory to be fulfilled, a good optimization strategy also needs to consider effects on time and costs, which are in close relationship.

In most cases, bolt force variations and local shape optimization is most interesting to evaluate regarding additional costs. Other variables such as pattern changes of bolts or runners as well as introduction of additional spacer which also dictates longer bolts have possibly negative effects on costs by necessitating process and tooling changes. A manual shape optimization can be directed to reduce part and/or production costs, however, associated with timely iterations as it includes CAD design changes with no guarantee of positive structural influences.

The main influencing parameter without intentional change of any given design feature is the bolt force. Initial analysis including suitable minimum and maximum bolt pretensions give relevant information of the general system response. Results have to be reviewed regarding gasket sealing pressure and lifetime.

Very beneficial is also automatic shape optimization, which is a powerful tool for lifetime improvement and for contact pressure optimization. Recently, FEV has developed a very unique process chain [19], especially regarding lifetime improvement. The process chain consists of the following cycling steps:

- Thermo-mechanical analysis (ABAQUS)
- Results evaluation (FEV-LowFat)
- Shape optimization (TOSCA)

An overview regarding a closed loop optimization is given in Figure 6. After initial global model analysis, one or more sub-models are built around critical areas. Those sub models are used for detailed shape optimization regarding lifetime.

The use of sub-models has the advantage that the analysis time for each optimization cycle is reduced drastically. Thermal and mechanical analyses are carried out for each optimization cycle, where the local shape of a critical area is modified in order to reach the predefined target. The target can be based on any lifetime prediction approach given in section **TMF Lifetime Prediction**, but also the minimization of plastic strain amplitude or mean and amplitude stresses. Hence, this process can also be used for TMF and HCF optimization of e.g. cylinder heads [20].

The optimized shape is a free form surface. For this reason the shape is given back to the design in order to create a producible surface close to the optimized design intend. The influence of the new geometry on the temperature distribution including possible small differences caused by implementation within the CAD system needs to be verified in a final analysis of the global model.

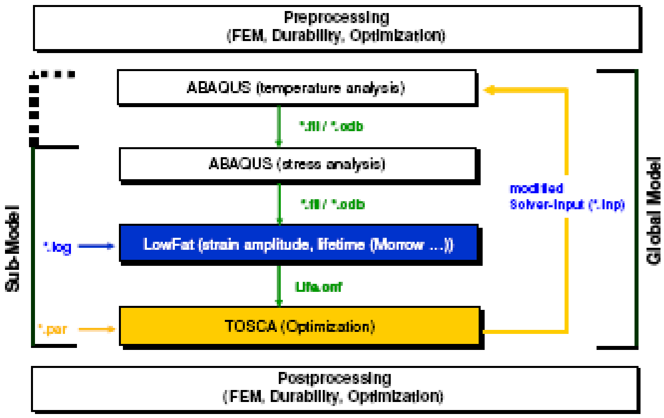

Figure 6: Closed Loop Optimization

OPTIMIZATION EXAMPLES

Global optimization within a closed loop analysis of the exhaust track leads to strongly reduced plastic strain. An example optimization of a crack location from the test bench runs correlated with the predicted high plastic strain amplitude is given in Figure 7.

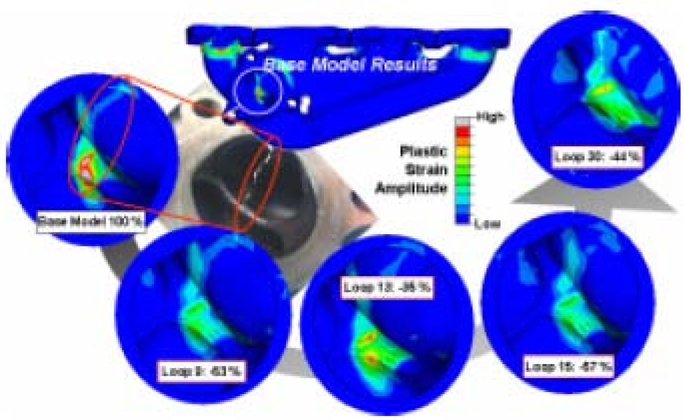

Figure 7: Plastic Strain Optimization (Global Model)

First, transient thermal analysis followed by a quasitransient structural analysis using elastoviscoplastic material behavior is compared to steady-state thermomechanical analysis with elastoplastic material behavior. The prediction of critical region with the latter approach allowed for faster optimization iterations. Since absolute life prediction has no physical meaning in this sense, the optimization variable is selected as the plastic strain amplitude. The finite element model is constructed with a dummy cylinder head model and bolts with forces applied on pre-tension sections to represent the assembly boundary conditions. Then, the cyclic thermal response of the exhaust manifold is simulated to investigate the TMF behavior, followed by optimization iterations.

The extensive chosen design area is a challenge for TOSCA and results can fluctuate during analysis loops. Analysis results of the single loops need to be compared and weighted. A reduction of the design area to local critical regions can help to reduce the number of necessary loops as shown in the following example.

A damaged head flange gasket which was reproducibly detected on the test bench is shown in Figure 8. Within this troubleshooting scope of work, initial baseline analysis showed that gasket pressure was lost by increased number of load cycles. This was caused by local cyclic plastification of the exhaust manifold near the runner collector, resulting in cumulative flange distortion until leakage occurs.

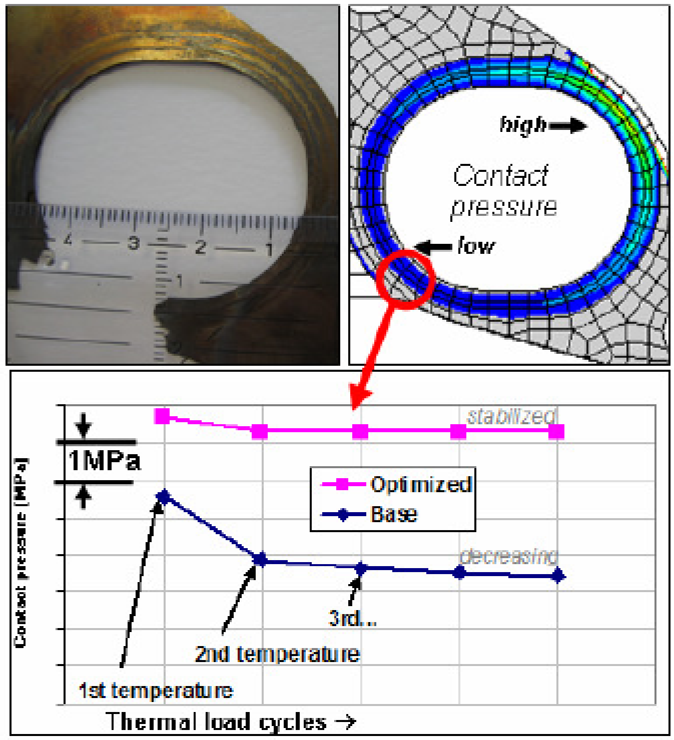

Figure 8: Gasket Leakage

In such cases, there are limited degrees of freedom regarding design and parameter variation. Bolt patterns and runner layout better not be changed due to cost and time reasons.

A solution was found by local automatic shape optimization (maximization of life span) followed by adjustment of initial bolt torque and a slight increase of flange and bolt height. Parameters that were explored during the optimization phase are bolt pretension, bolt height and gasket stiffness. Design options considered are mainly flange height and stiff connection of adjacent runners. The combination of the chosen options provided the most cost effective solution to an endurable gasket and manifold design, with a lifetime increase of 41% and a better distribution of gasket pressure (no leakage) as displayed in Figure 8.

The study provided a sub-model optimization example for a thermo-mechanically high loaded area between two runners under consideration of fatigue life (from FEVLowFat) as an optimization parameter. Thanks to sub-modeling technique, it was possible to run the optimization loops with a transient thermomechanical analysis due to the small size and reduced nonlinearity (only material nonlinearity) of the model. In this case, the assembly and temperature conditions already calculated in the global model analysis are interpolated as the deformations and heat fluxes at the boundary nodes of the submodel, allowing the optimization technique to be applicable with regard to engine development timeframe. Due to the detailed problem setup with in depth material characterization and consideration of transient thermal and mechanical loading, optimization is done directly using lifetime calculated with the modified energetic approach.

In the traditional modification process on the basis of CAD-variant constructions and their verification by means of FE modeling and analysis, the same improvement potential can only be achieved with much higher expense. The exhaust manifold shows the potential of reducing the time needed for the optimization from weeks to days. The provided example gives a real run time of 54 minutes for transient thermal analysis, 102 minutes for transient structural analysis, 20 minutes for lifetime post processing and less than 5 minutes for Tosca design changes per iteration, resulting in a total time of approximately 2 days per 15 iterations. This time scale is certainly on a different base as compared to traditional manual CAD design changes and succeeding calculations, which has a time scale in the order of a week per iteration. However, a final verification analysis in the global model is needed in case of sub-model optimization, because local stiffness changes can influence the sub-model boundary conditions.

In case of fabricated manifolds, special optimization techniques are required. A general shape optimization would lead to an inhomogeneous metal sheet thickness, which is not possible for fabricated manifolds. Slight differences in sheet thickness are a result of the metal sheet forming process. During the optimization process the wall thickness of the sheet metal needs to be kept constant. This can be carried out by either using shell elements, where the material thickness is a parameter or by linking interior and exterior nodes in order to follow the same shape, i.e., constant wall thickness.

To underline, the free form optimization degree of freedom in cast manifolds does not exist in case of fabricated manifolds. Therefore, the gain in terms of strain or stress reduction, realized by shape modification, is limited for fabricated manifolds. This of course generates a challenge and gives more importance to the problem description, which in turn impacts the solution efficiency.

A critical area was found in an air gap isolated manifold at a bolting tool access area. The critical region could not be modified directly because of the inner sheet metal located in direct vicinity on the inner side and the tooling accessibility of the bolting tool for assembly on the outer side.

A solution was found by defining the design nodes for optimization in the modifiable area near the critical region (the neighboring 3 node columns adjust their deformations accordingly). After only a few iterations it became obvious that moving the outer sheet outwards results in an increase of lifetime. The achieved shape was implemented to the CAD-model, where transition radii were maximized. This design was then finally analyzed in global and sub-model. Thus, the influence of possible sub-model boundary errors was removed.

In summary, successful application of the analysis and optimization package developed to ensure structural integrity of thermo-mechanically loaded engine components is granted in the case of exhaust manifolds. This package integrates several disciplines and philosophies and allows an interaction of tools designed for problem descriptions in CAE platforms, solver, life calculators, optimization programs and databases.

The process starts with exhaust manifold type and material selection, if not defined already, or with an evaluation of existing definitions by using benchmarking and databases. The selected material is replicated with Abaqus built-in material models activating the necessary parameters, and these parameters are identified by using FEV_ParFit to get a satisfactory fit to experimental results.

The concept design analysis can be done with simplified thermal boundary conditions or with boundary conditions from CFD analyses, which are mapped onto the FE mesh by FEV_CFD2ABA. A transient thermal analysis, corresponding to the test cycle defined by FEV_MASTER – a tool utilizing statistical techniques to define B10 equivalent test conditions – can be validated with thermocouple measurements if the hardware is existing. The following structural analysis identifies the potential critical regions and provides the stress-strain response used for lifetime calculation by using a proper life criterion. A target-oriented optimization with the corresponding modeling abstraction level can be conducted on a global model level or sub-model level. The fatigue evaluation programs FEMFAT and FEV_LowFat are linked to TOSCA and FEV_OptDat for closed loop optimization.

CONCLUSION

This study provided a procedure for an integral solution, which provides for the development of optimized exhaust manifolds that are failure-free.

Accurate material and lifetime modeling, when used in combination with correct representation of dominant loads and assembly constraints, enables reliable predictions for the failure behavior of exhaust manifolds. In addition, automatic shape optimization provides a powerful tool for the development of exhaust manifolds. Conversely, engineering expertise is required to ensure proper use of this technique.

Different techniques are needed for the optimization of cast and fabricated manifolds, because of production restrictions. This problem is already been addressed and a procedure has been implemented. The manual and automatic optimization methods have distinct advantages and disadvantages. A cost effective solution is delivered by a combined methodology, which also results in a failure-free exhaust manifold design.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

b	Fatigue strength exponent
β	Accumulated energy to fracture exponent
c	Fatigue ductility exponent
C	Accumulated energy to fracture parameter
E	Youngs modulus
ε_f	Fatigue ductility coefficient
$\varepsilon_{mech,amp}$	Mechanical strain amplitude
$\varepsilon_{m,t}$	Mean total strain
$\varepsilon_{pl,amp}$	Plastic strain amplitude
N	Number of cycles
σ_f	Fatigue strength coefficient
σ_m	Mean stress
σ_{max}	Maximum stress
ΔW	Energy dissipated per cycle