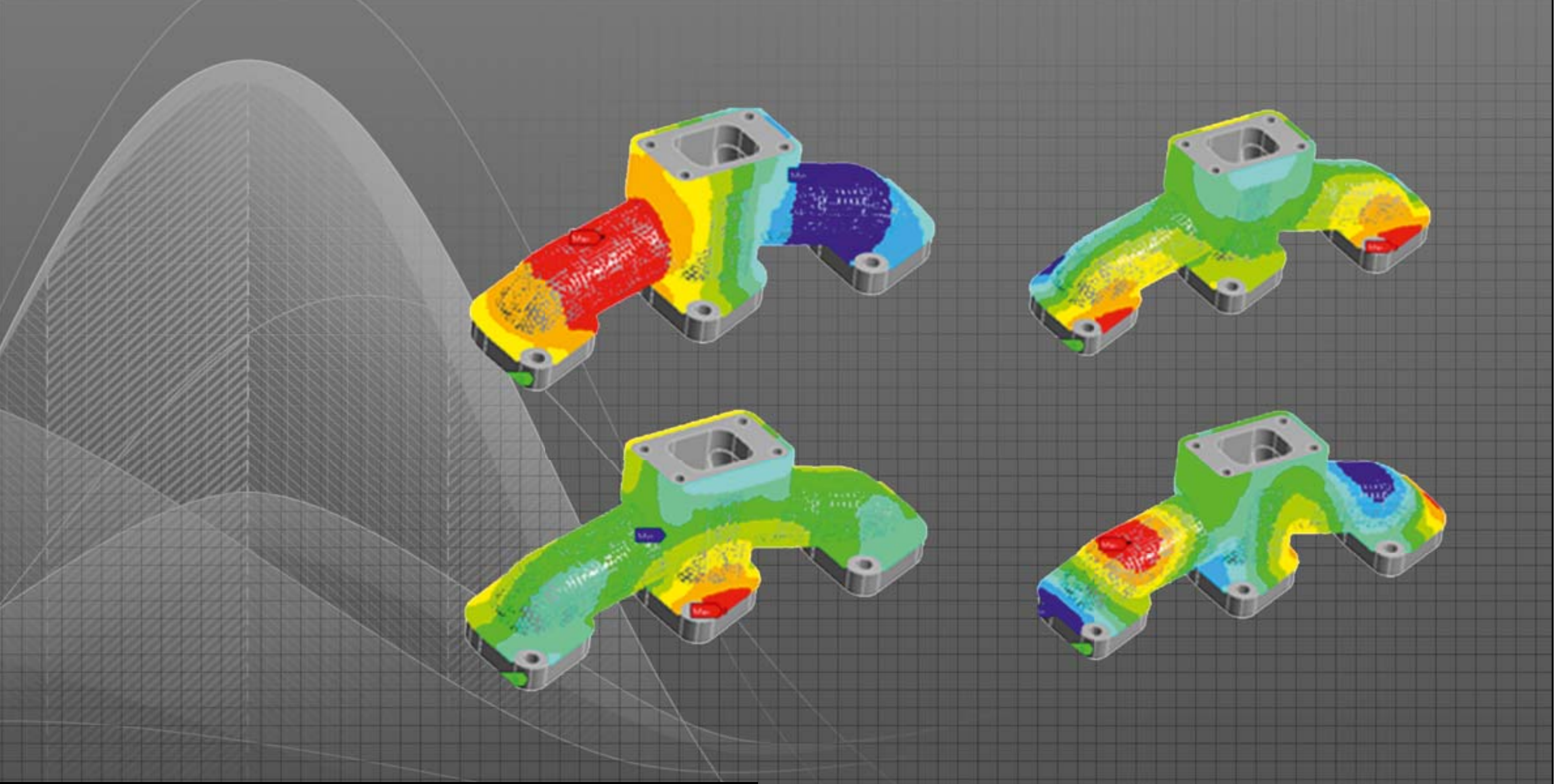

SENSITIVITY ANALYSIS OF THERMO-MECHANICAL FATIGUE LIFE OF AN EXHAUST MANIFOLD

ANSYS India conducted a reduced order model based sensitivity analysis of thermo-mechanical fatigue life of an exhaust manifold subjected to uncertainties in material, loading and manufacturing.

Introduction

Exhaust manifold components in the automotive industry are typically subjected to high thermo-mechanical cyclic load and prone to fatigue failure. Location of minimum life varies with mainly three factors – inaccurate determination of material model coefficients, thermo-mechanical load variation and manufacturing variability such as uneven thickness of the manifold wall because of the casting process. Manufacturing variability is random in nature and difficult to address through deterministic CAD model change and to be re-run as an entire simulation for life estimate of components. At the same time, a large number of prototype casting and testing incurs huge cost.

This article describes a model order reduction technique to quantify the spatially distributed manufacturing variability using random field shapes for component wall thickness variation combined with mesh morphing to produce different geometries. As the material yield points often could not be determined with confidence, field models are used to generate additional random parameters. Also, randomness of the peak cyclic temperature and corresponding convection film coefficients are represented by random input parameters. Minimum fatigue life and its location is identified from a quantile plot over the component surface. Finally, the sensitivity for the minimum fatigue life is estimated using a variance based sensitivity analysis. In the following two sections, material modeling and fatigue life estimation using crack tip opening displacement (CTOD) methods will be described briefly. Finally, a quantification of uncertainty will conclude the study.

Selection of Material Models

Selecting the right material for different parts of the component form is a critical element to design for Thermo-Mechanical Fatigue. It is important to characterize how this material behaves when exposed to different loads and conditions. For material characterization, the usual procedure would be to capture through physical testing of coupons how the materials behave at different temperatures, strain ranges, strain rates, dwell periods, different phases between thermal and mechanical strain, environments, etc. Rate effects are dominant at temperatures higher than half the homologous temperature. Furthermore, isotropic work hardening is more dominant at lower temperatures.

The effect of strain rate is captured through a viscoplastic model, which essentially follows what is known as the over stress model. At very slow plastic strain rates, a characteristic of this model is to follow the rate independent plasticity. In this case, the stress is at the yield surface. The applied model has multiple layers and is able to capture the viscoplastic behavior at different stress levels.

Kinematic hardening captures the Baushinger effect, where the centre of the yield surface moves in response to plastic strains. At this centre, kinematic hardening represents the back stress in the system. In these alloys, this movement has a distinct non-linear behavior and, similar to work hardening, has a limiting surface to which the yield surface can move to. The implementation of the Chaboche model (Chaboche, 1989) (Chaboche, 1981) is able to capture these characteristics accurately. As an additional rate effect, the back stress, which manifests as self-equilibrated microscopic residual stresses (Lemitre & Chaboche, 1990) at grain boundaries, becomes diffused and released if kept at high temperatures for some time. This causes the centre of the yield surface to drop back to its initial original state over time. This drop follows a nonlinear behavior and is a strong function of the back stress itself. This rate effect is captured by enabling the static recovery term (ANSYS Inc, 2018) in the Chaboche model. Since the material has been characterized, the next step is to study what does the component experience as it goes through the duty cycle. If reality is mimicked in total, it would take a very long period of physical time to solve this task potentially, which would not be practical. In industrial practice, therefore a representative cycle approach is applied. Essentially, this means to look at the experience of the component through a duty cycle somewhere during its life. Often this is conducted at mid-life cycle. Then life is calculated based on the damage that happens in this cycle.

Life Calculation

Methodology

In this study, fatigue life calculation is based on CTOD (Crack Tip Opening Distance). Typically, due to presence of high temperature, the amount of inelastic strain in the component is considerable. Due to a huge plastic zone ahead of it, the crack tip becomes blunt. As the load is increased, the blunting increases and, after a threshold value of stress, the blunt tip opens up, i.e. crack propagates. He et al (He et al, 1981) analytically calculated the expression for J-Integral, consisting of separate elastic and plastic parts, for penny shaped cracks.

Opposed to stress values, strain values are computed between two time points in the stabilized cycle load-step. The two time points are shown in Fig. 1. The TMF damage is determined from J-integral. From damage, the fatigue life is calculated.

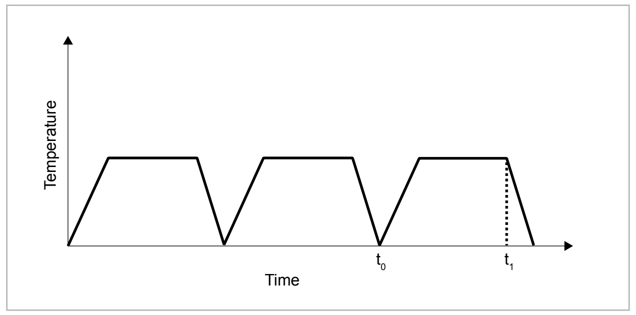

Fig. 1: Time points selected to find the difference in stress tensors

Life Calculation Results

During this study, the component was subjected to temperature cycling as shown in Fig. 2.

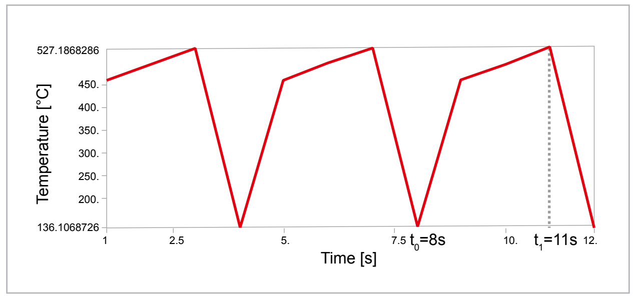

Fig. 2: Temperature profile

The plastic strains stabilized in the third cycle. The time points for calculating the stress and strain amplitudes were selected as t_0=8s and t_1=11s. From the stress and strain amplitudes, the damage was calculated for the stabilized cycle. The life was then calculated for each element.

While reporting life, the bolt locations were excluded from the model. Bolt locations mostly had high stress concentration and singularity as shown in Fig. 3. Also, the critical location based on the deformation pattern appeared at the bends.

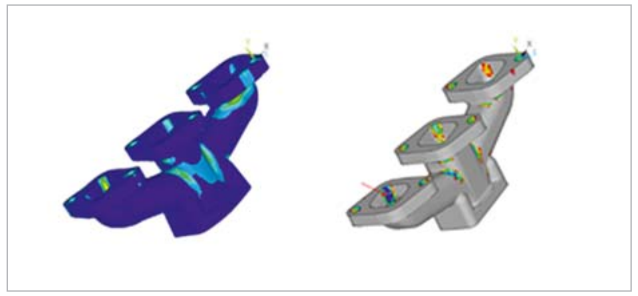

Figure 3: Plastic strain (left) and life plot (right)

Low life regions mostly appeared at bend. Further the life and strain plots showed 180-degree rotation symmetry. Afterwards, as described in the following section, a sensitivity analysis was performed to identify the critical input parameters responsible for minimum fatigue life.

Uncertainties in Exhaust Manifold Design

In this study, yield stresses at five temperature points (20, 300, 500, 550 and 6000C) were given a ±10% variation on the respective reference values. Additionally, the highest cyclic temperature was given a ±10% variation on the reference value of 6000C. A variation of ±10% was also considered for the convection film coefficient at the inner surface of the manifold. Manufacturing defects or nominal variation of the geometry from the casting process were accounted through a special morphing technique clubbed with statistical formulation of the spatially distributed randomness as described below. ANSYS optiSLang along with Statistics on Structures (SoS) was used to generate the random fields and to perform the sensitivity analysis as well as the uncertainty quantification.

Random Geometry Generation through Mesh Morphing

A synthetic random field parametric model, representing possible uncertainties in geometry, was generated on top of the nominal mesh of the idealized perfect geometry model. The outer surface of the exhaust manifold was provided as the surface mesh to be morphed using the synthetic random field model. To generate the synthetic random field for every surface nodal point, max/min normal movement was defined using a standard deviation value. An internal autocorrelation matrix based on the distance between nodes was solved in an eigenvalue analysis and its eigen shapes and related distribution of amplitudes were generated. Eigen shapes represent variation shapes (scatter shapes) of outer surface of the manifold as shown in Fig. 4. Positive and negative values within an Eigen shape indicate outward and inward normal movement of the node. A selection from the resulting Eigen shapes was used in the morphing process of the surface nodes. Each morphing shape together with mesh relaxation techniques was tested separately to ensure that the element Jacobian ratios were maintained for accuracy of the finite element solution. The first 14 shapes were used for the random field parametric model. They were able to explain any arbitrary variation of the manifold outer surface representing 95% of total possible surface variation. To generate imperfect surfaces, the shapes were multiplied with random amplitudes and combined algebraically so that at every node the target input standard deviation value was not exceeded.

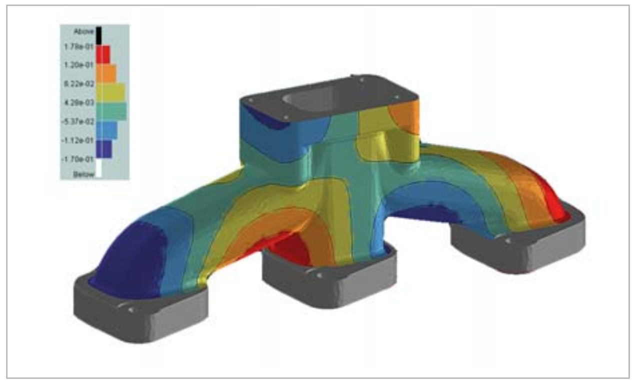

Fig. 4: Eigen shape contour showing normal movement of node

Sensitivity Analysis

Using the 14 random amplitudes of the Eigen shapes and additional random parameters, in total 21 uncertain parameters were considered and their effect on the fatigue life was studied using a sensitivity analysis plus uncertainty quantification. A Latin Hypercube Sampling scheme was used for the Design of Experiment and 95 design point results were accomplished. The location of the minimum value of life was identified from a quantile plot over the manifold surface of 95%, i.e., there was 5% probability of exceeding the plotted minimum life values. Five such critical hot spot locations were identified where the life values are low. They are shown in the quantile plot Fig. 5.

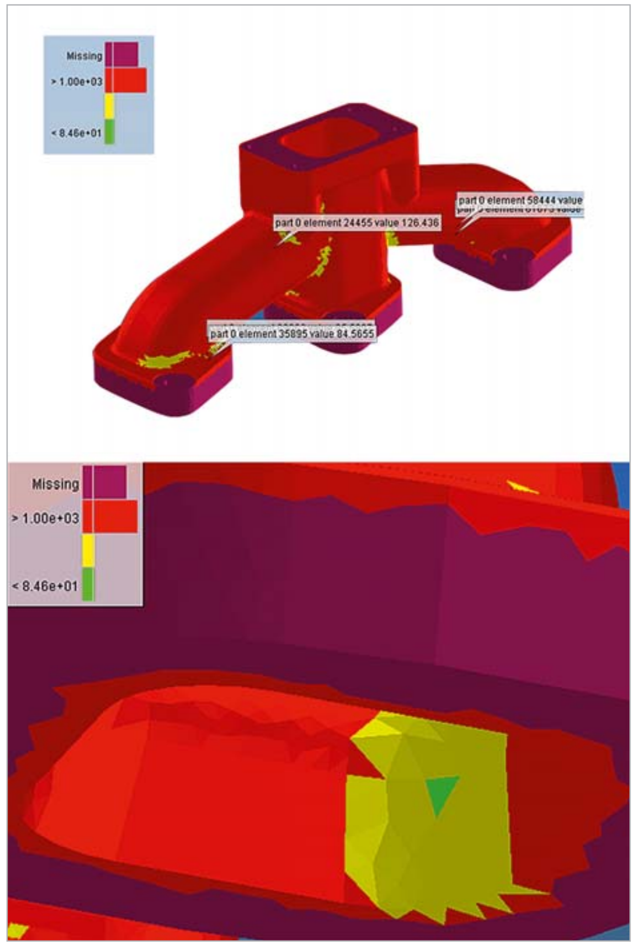

Fig. 5: 95% quantile plot for fatigue life

Hot Spot Sensitivity

For the above mentioned five locations, a sensitivity analysis based on the 95 design points was performed. The sensitivity of minimum life is plotted in Fig. 6 for the location shown in Fig. 5. The peak cyclic temperature and film coefficient were the most influential input parameters and followed by four geometry scatter shapes, which had the largest influence on the variability of the life estimate.

Fig. 7 shows the distribution of change in thickness of walls for the sensitive shapes 2, 10, 11 and 13. It could be observed that all the above shapes were changing the thickness at the minimum life location shown in Fig. 5.

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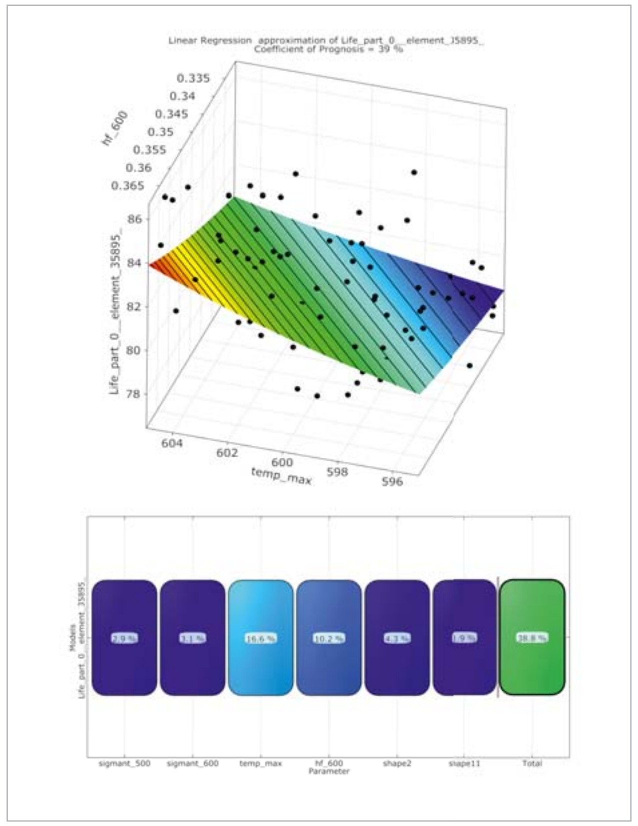

Fig. 6: Metamodel of Optimal Prognosis for minimum life location

The forecast quality of the variability of minimum life on the response surface was only around 60% as shown in Fig. 6. The reason can be attributed to multiple facts. Firstly, 95 runs may not be sufficient for the sensitivity analysis with 21 parameters. It may require some more runs to improve the forecast quality of the metamodel. Secondly, linear tetrahedral coarse mesh was used for the acceleration of the study. This might introduce locking in the mesh and noise for the response quantities, which could lead to lower prediction quality. Thirdly, the metamodels were generated for five positions of expected minimums. In case the minimum locations are moving as a result of input variability, the extraction process may add the same additional noise to the results.

CONCLUSION

In this study, a generic uncertainty quantification approach is presented to counter the randomness in nonlinear material modeling, thermo-mechanical loading and manufacturing tolerance altogether. A quantile plot based assessment of the minimum crack location and the corresponding sensitivity analysis helped to identify the important variables, which can change the location of cracks and often make it vulnerable in-service life. The uncertainty quantification in life was performed on the base of the Latin Hypercube sampling.

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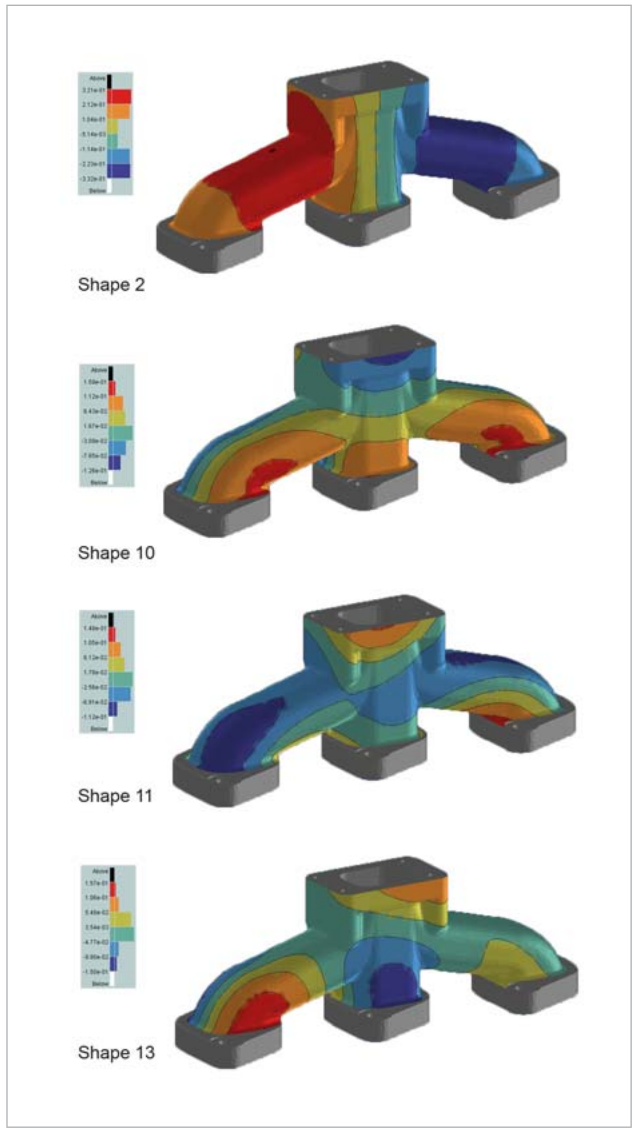

Fig. 6: Metamodel of Optimal Prognosis for minimum life location

Acknowledgement //

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