

TMF Lite Process Development

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Abstract: A simplified manifold transient thermal analysis method has been developed and used in engine design and validations. Traditionally full-blown manifold transient thermal analysis has been performed using CFD and it will take weeks for completion. In this simplified method, a user subroutine film.f is used to define the htc and gas temperature at manifold surfaces so that the transient thermal analysis can be performed in Abaqus quickly. The method is designed to reduce the simulation time significantly by sacrificing some accuracy. A comparison study showed that the simplified simulation results can capture the general trend in temperature distribution and can be used in thermal stress and fatigue analysis for quick design evaluations during the early design stage when many design versions need to be compared in a short time as in the case for Tier 4 manifold design. The simulation time has been reduced from weeks to days. It proved to be a good alternative to full scale CFD analysis when many design versions need to be compared at the early design stage.

1. Introduction

TMF represents thermal mechanical fatigue analysis which is mainly used in engine components which experience significant high temperature in service like in manifolds. An accurate TMF life prediction is based on accurate transient temperature predictions. Currently, the best method for predicting these temperatures is a conjugate (i.e., fluid and metal) transient CFD analysis of the exhaust manifold system. This analysis incorporates a portion of the cylinder head, the exhaust manifold, fasteners, and turbine housing, and it accounts for spatial variation in metal-fluid boundary conditions as well as temporal variation through the cycle. The typical TMF thermal cycles and standard TMF process are illustrated in Figure 1 and 2.

The drawback to an exhaust manifold CFD is that it is quite time-consuming. A model of this complexity typically takes two to five weeks to complete. Such time duration is not quick enough for rapid design iterations in the early phase of manifold design process. The purpose of the TMF “Lite” process is to simplify the TMF analysis of an early manifold design such that the analysis completion time is one week or less. A key to this compressed time schedule is bypassing the CFD by using a simplified FE-based thermal transient analysis.

An Abaqus user subroutine film.f has been developed to define the heat transfer boundary conditions in the center section of the manifold. It reduces the heat transfer analysis time and overall TMF analysis time significantly. Fatigue analysis results comparison showed that the Lite process can capture the general pattern of fatigue life in the center section and can be used in the early design stage.

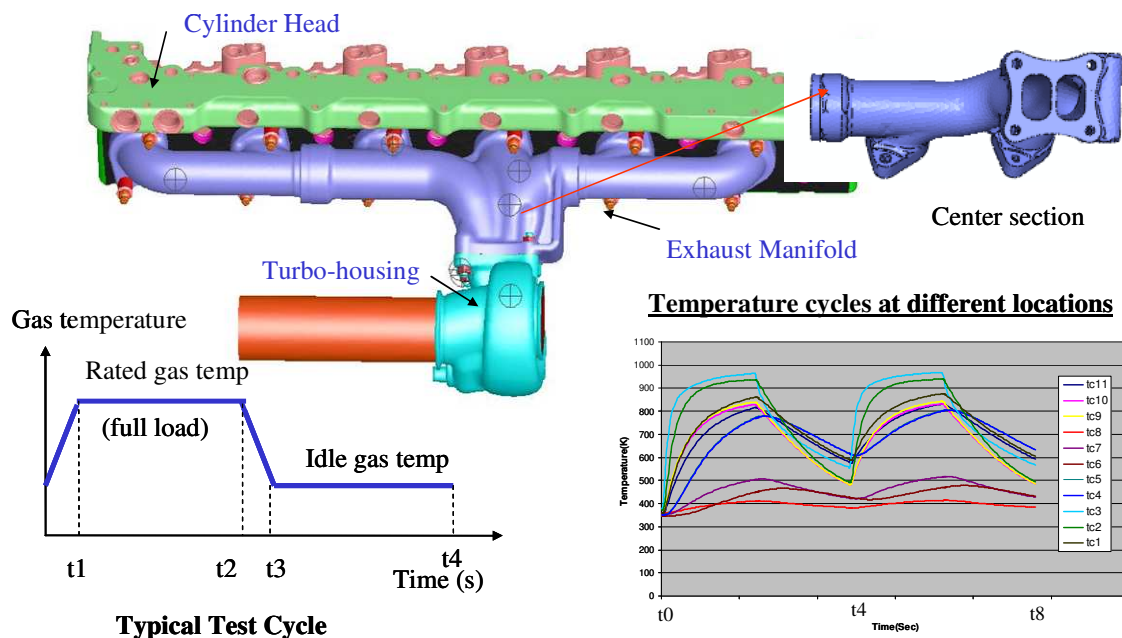


Figure 1. Typical TMF Thermal Cycles

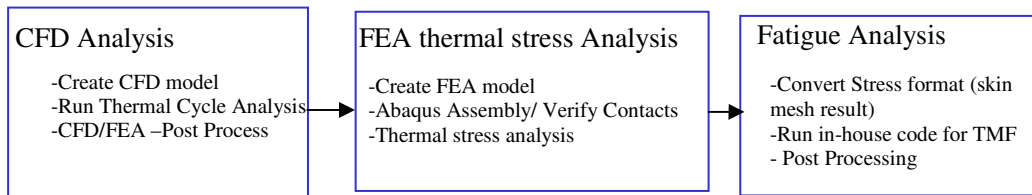


Figure 2. Overview of Standard TMF Process

2. Lite Model Development

The procedure was specifically developed and validated for exhaust manifold center sections of mid-range and heavy-duty diesel engines with in-line cylinder design. As shown in Figure 3, only center section is analyzed for thermal analysis and structural analysis instead of full CFD analysis and full structural analysis. A transient heat transfer analysis is performed in Abaqus to replace CFD analysis to save simulation time. An Abaqus user subroutine film.f has been developed specifically to define the heat transfer boundary conditions for the internal ports in the center section of the manifold.

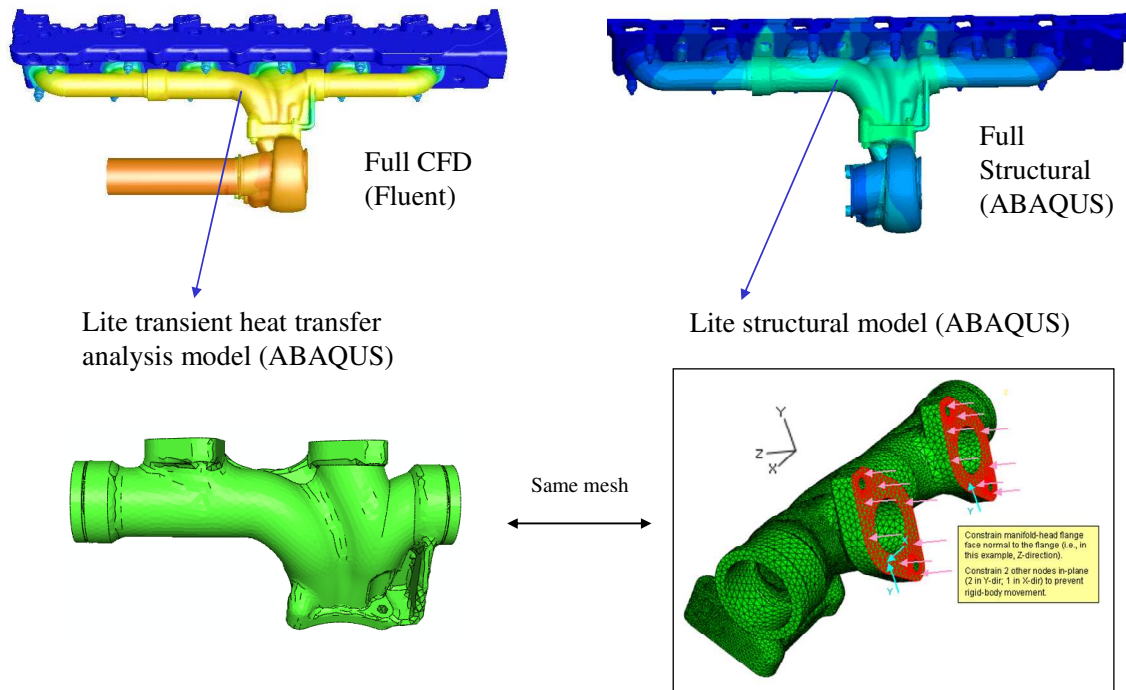


Figure 3. Full TMF and Lite TMF Model

2.1 Structural Boundary Conditions

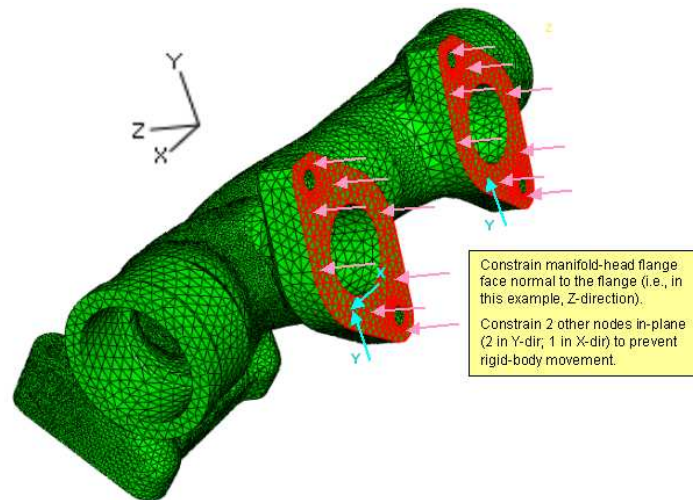


Figure 4. Full TMF and Lite TMF Model

Figure 4 shows simplified structural boundary condition for the center section.

2.2 Thermal Boundary Conditions

2.2.1 External Thermal Boundary Conditions

The thermal boundary conditions are in the form of a heat transfer coefficient (HTC) and fluid temperature (T). The external boundary conditions are fixed (as shown in Figure 5). The values for the external surface, for the manifold-to-head joint surfaces and for the slip joint surface were determined by matching results to a full TMF analysis of a manifold center section.

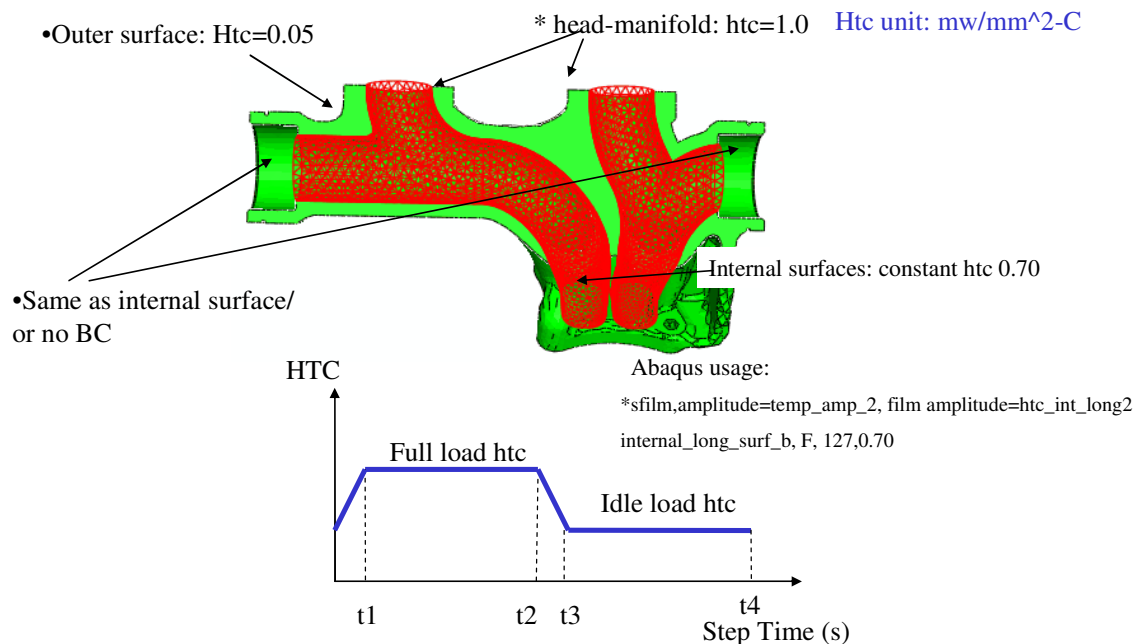
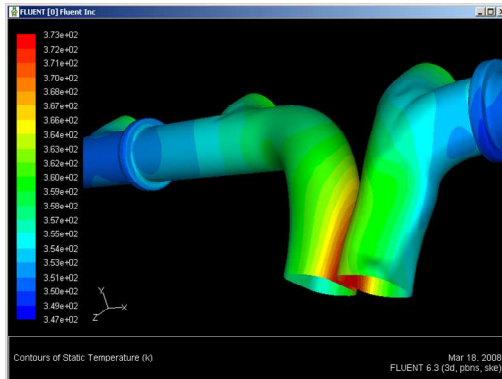


Figure 5. Initial Lite Model Assumption

2.2.2 Internal Thermal Boundary Conditions

The internal boundary conditions vary with time, and they are meant to be simplification of the Diesel Engine Exhaust System Durability Test. Different methods have been proposed and evaluated. The initial method was to assign a fixed value (an average value based on CFD analysis) for the entire internal port. The comparison of temperature contour plots between CFD results and initial simplified method shows that while the initial simplified method can capture the general trend, there are obvious temperature differences at some thermal couple locations.

In order to further improve the simplified method, the method of defining the internal htc with Abaqus user subroutine film.f was developed. It was designed in a way that the internal passage is divided into different regions and each region is assigned to a different htc based on the exhaust air flow as shown in Figure 7.



CFD

- v Idle temperature contour from CFD
- v The goal is to map CFD steady results with a set of heat transfer BC

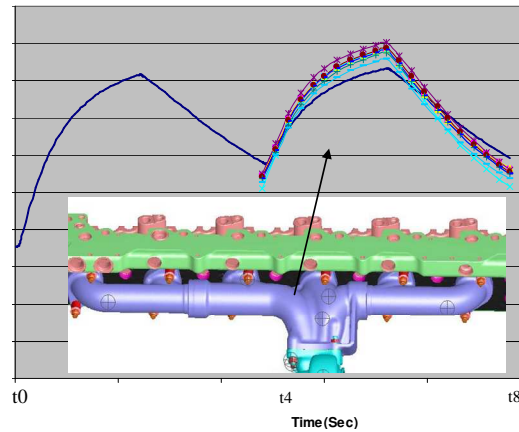
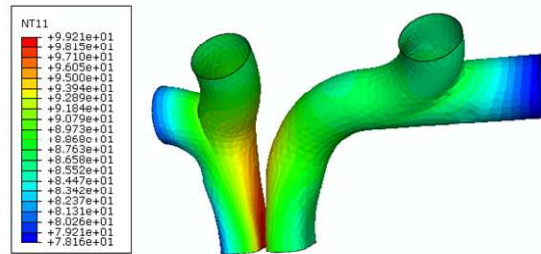


Figure 6. Comparison with CFD Results

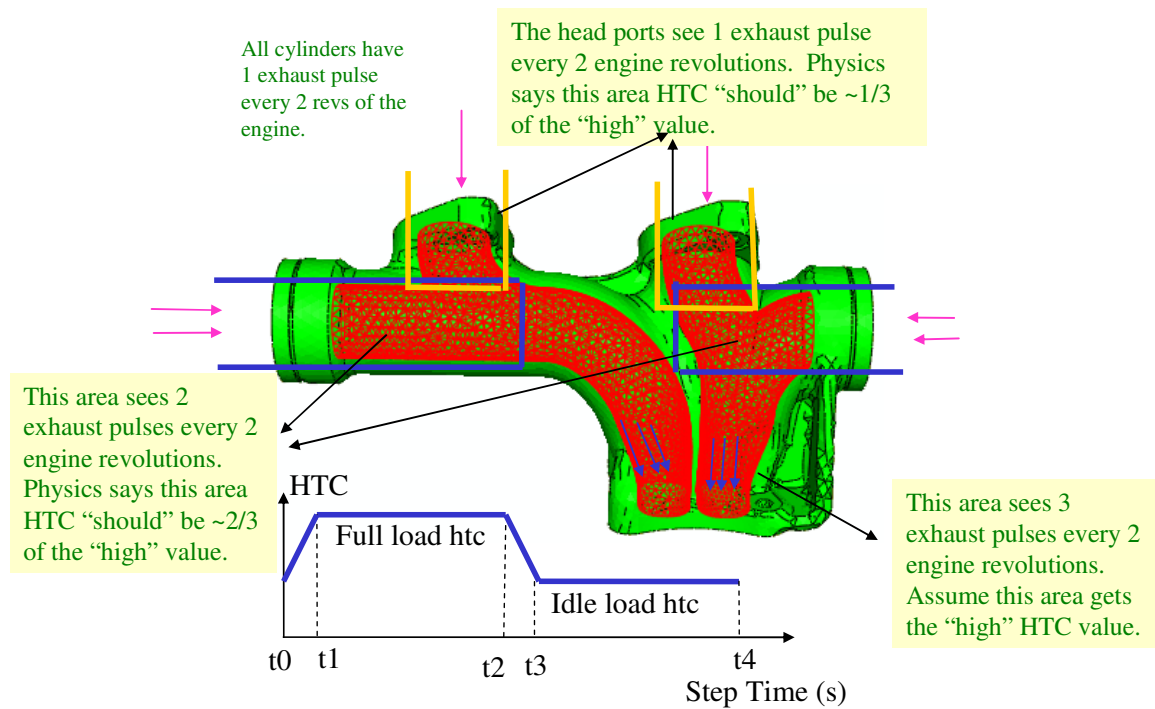


Figure 7. Abaqus User Subroutine film.f Development

In Abaqus user subroutine film.f, the first task is to divide the internal ports into different region automatically. This was done by asking FEA analysts to enter some coordinates at specific nodes like in the OD of the port interface as shown in Figure 8. With these nodal coordinate inputs, the internal passage was divided into several regions and assigned different htc values.

In order to verify whether the right htc was assigned to the right region, the htc values assigned were written into user variables using Abaqus user subroutine UVARM and displayed in Abaqus/Viewer. In this way it was verified that intended htc values were assigned to the right regions.

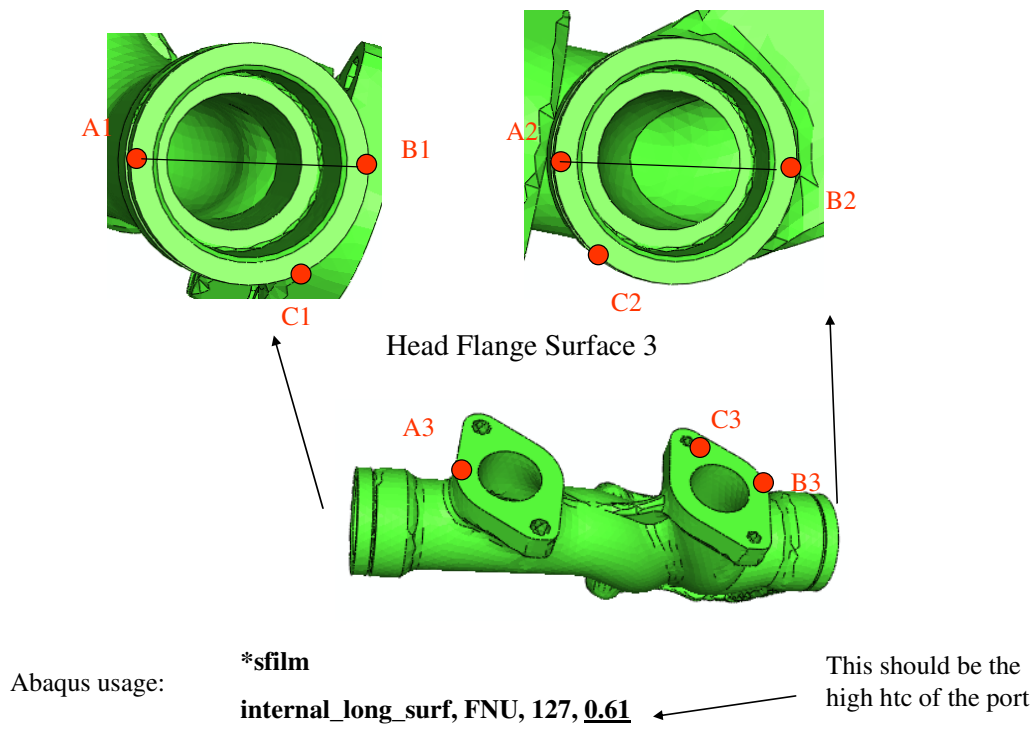


Figure 8. Input for Abaqus User Subroutine film.f

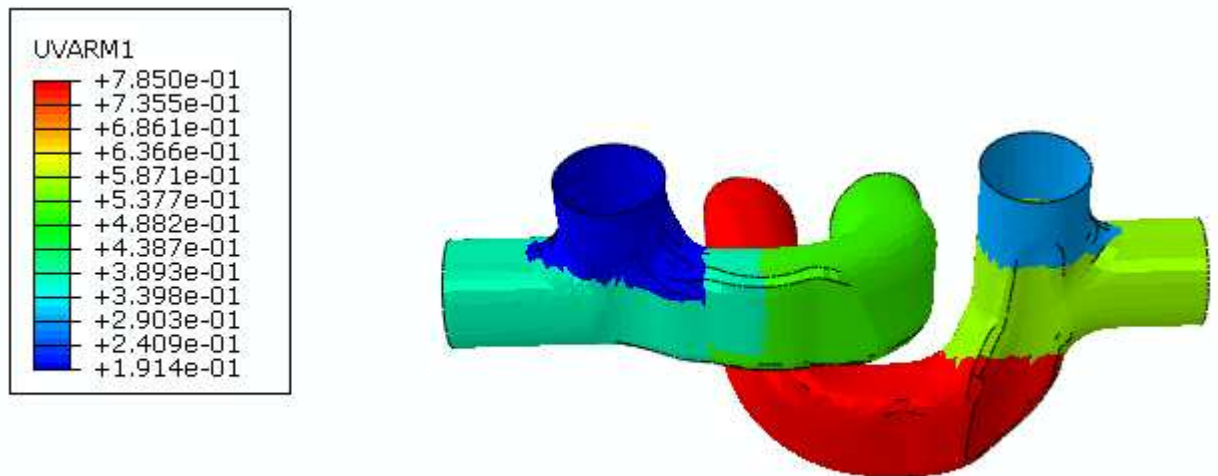


Figure 9. Verification of HTC Using User Subroutine UVARM

2.3 Temperature and Fatigue Results Comparison

Temperature comparison between CFD and Lite Models (fixed htc method and user subroutine method) is shown in Figure 10. It is shown that temperature difference between CFD results and Lite model is reduced significantly with the use of Abaqus user subroutine. The max temperature difference at key thermocouple locations is less than 20C.

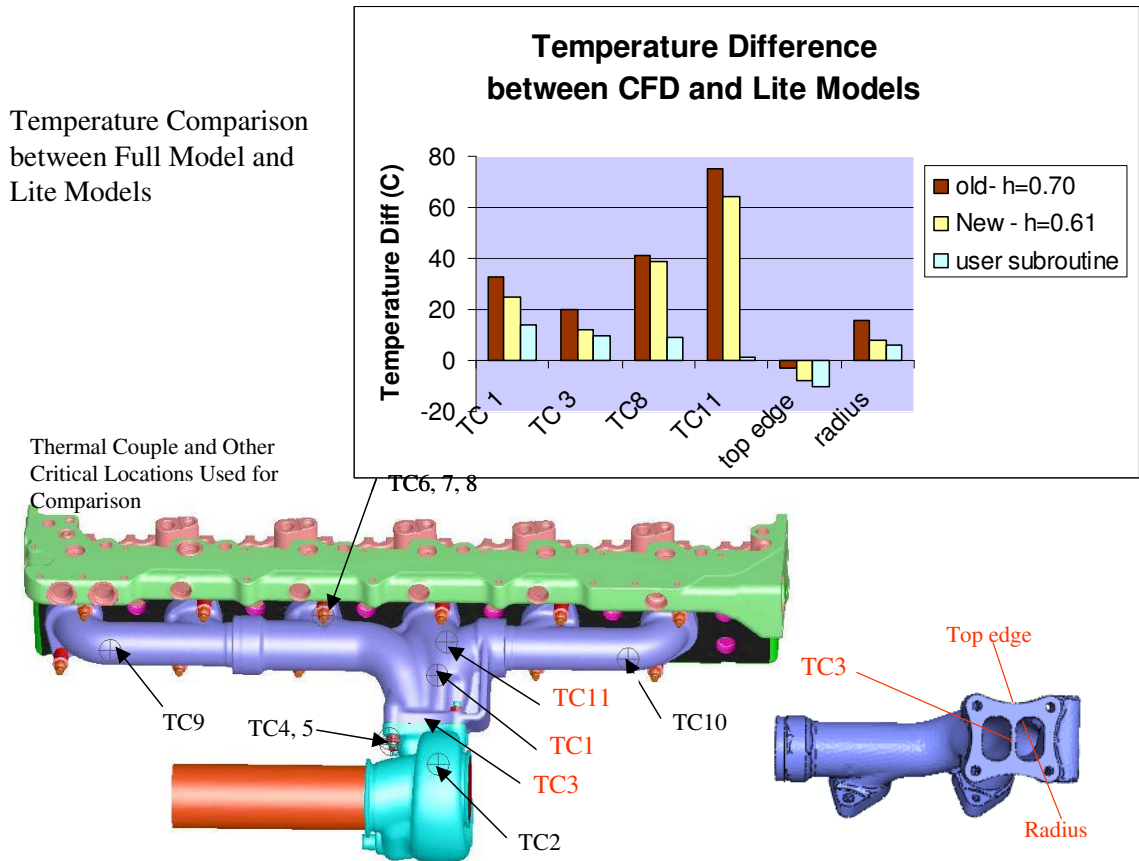


Figure 10. Temperature Comparison

Thermal fatigue analyses were performed also based on thermal stresses from both full TMF and TMF-Lite. The fatigue life results were compared at critical locations (shown in Figure 11). Comparison of the fatigue results is shown in Figure 12. The X axis shows the life predicted by using full TMF while y axis represents life predicted using TMF-Lite procedure. It is shown that most data fall in the range of one order of magnitude, and that more than 70% of data are below Full TMF results. It also shows that the data which exceed full TMF results are less than 2x of the CFD results. Therefore the model is generally conservative.

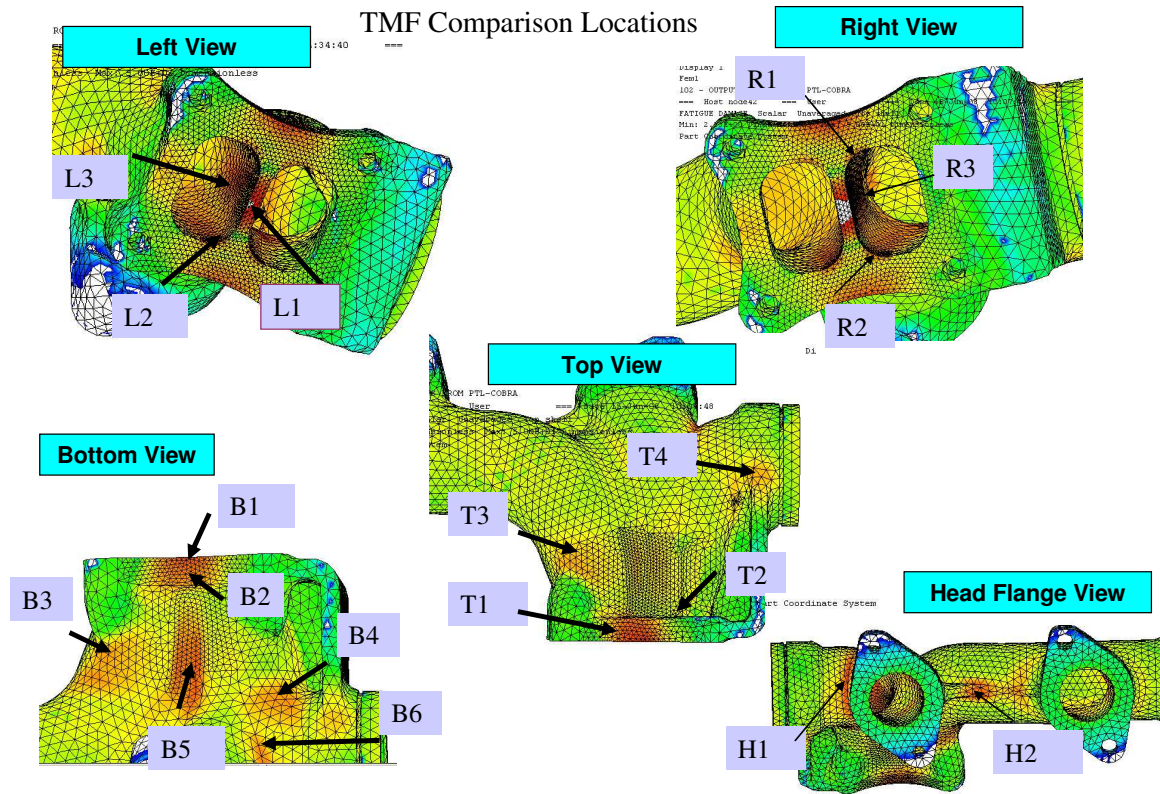


Figure 11. Fatigue Results Comparison Locations

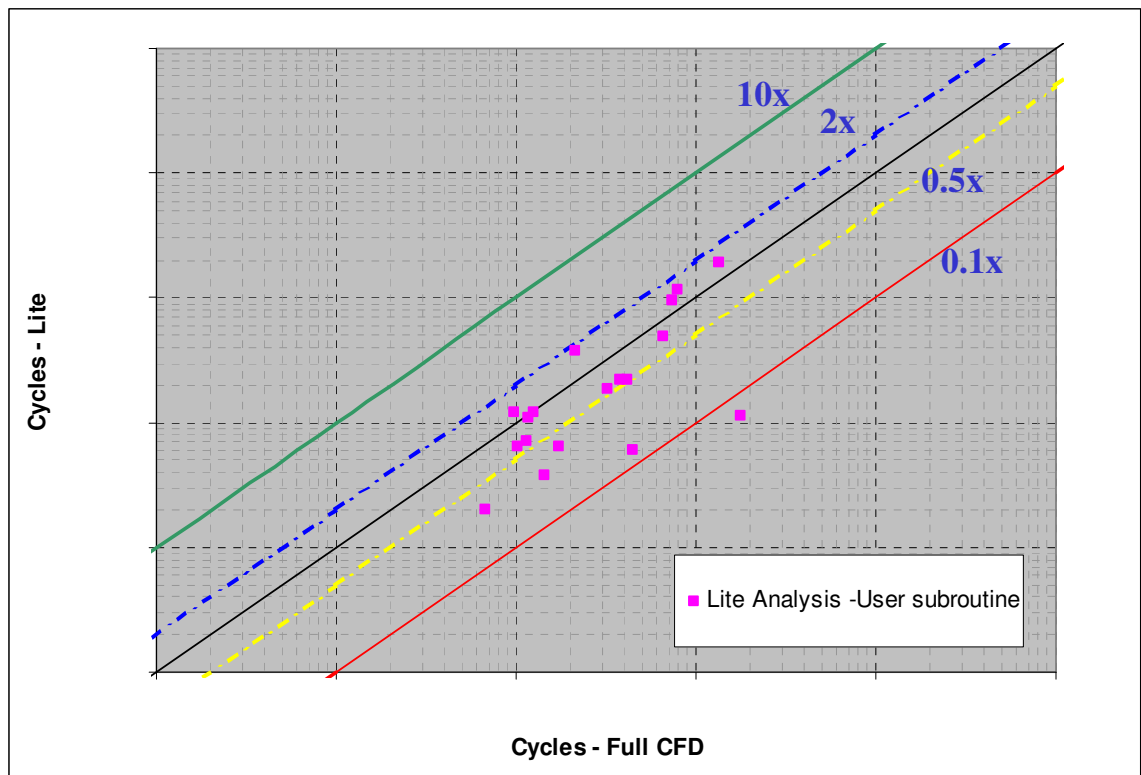


Figure 12. Fatigue Results Comparison

3. Conclusion

- A. A TMF Lite Procedure has been developed and verified; Its advantages / limitations defined;
- B. Lite Process significantly reduces the TMF analysis time to 3 ~ 5 working days (Transient FEA + Stress FEA + TMF) from about more than 3 weeks for the full TMF;
- C. This process has been incorporated as an important part of the overall manifold validation strategy;
- D. TMF Lite procedure has been used in the validation of Tier 4 exhaust manifold designs.