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Design and Analysis of Exhaust Manifold in Diesel Engine

Agilesh. A[1], P.Pichandi[2]
[1]*Department of Engineering Design,* [2]*Department of mechanical engineering*
JCT College of Engineering and Technology, Pichanur, Coimbatore.

Abstract-This project aims in re-designing an exhaust manifold by determining the thermal stresses and deflections exhibited under various operating conditions with different materials and temperatures. The objective is to ensure the suitability of the design for a particular material from the view point of reliability and serviceability. Defects in existing manifold are cracks usually occur due to prolonged exposure to extreme temperatures, defects in casting and repeated heat cycling. Welded regions and the curved profiles are the critical regions of failure. A methodology is developed to ensure the best suited design and material for the given operating conditions. Manifold behavior for Cast Iron is analyzed. Redesigning the curved profiles can reduce the turbulence effect of the exhaust gases on the welds. High-end CAD/CAM software such as Cero3.0 and ANSYS 14.0 are used for modeling and analysis.
Keywords: Exhaust manifold, Cast iron, Metal matrix, Turbulence effect, Thermal stress

I. INTRODUCTION

Finite Element Analysis is used to investigate the associated thermal stresses and deformations under extreme operational conditions which replicate the actual physics of the model. Analysis carried out by reference environmental testing conditions; in different ambient temperatures on different materials i.e. cast iron, structural steel. The finite element analysis software ANSYS 14.0 is used to calculate the linear steady state temperature distribution under the thermal field & structural analysis. Thermal analysis calculates the temperature distributions and related thermal quantities in an exhaust manifold. Structural analysis takes inputs from thermal analysis to calculate deformation, stress and strain.

FEM analysis is done by using tetrahedral element of first order and convergence test is performed for structural load. The purpose of this analysis is to ensure the appropriateness of material for the defined design from the view point of serviceability of the exhaust manifold. Selected details and results of the overall investigation are presented and discussed within the framework of this project.

II. EXHAUST MANIFOLD

Exhaust manifold is a part of diesel engines which are required to collect the exhaust gases from the cylinder head and send it to the exhaust system. The exhaust manifold plays an important role in the performance of an engine system. Particularly, the efficiencies of emission and the fuel consumption are nearly related to the exhaust manifold. The manifold may be a casting or fabricated of relatively light material. The purpose of the exhaust manifold is to collect and carry these exhaust gases away from the cylinders with a minimum of back pressure. Exhaust Manifolds are affected by thermal stresses and deformations due the temperature distribution, heat accumulation or dissipation and other related thermal quantities. The objective of our analysis is to find out the suitable material by comparing thermal stresses and deformations induce by temperature mapping on different materials for exhaust manifold of off-road vehicle diesel engine. In this project we investigate an exhaust manifold of an off-road vehicle diesel engine. In First Step, FEM analyses are done on a component by using tetrahedron element of first order and convergence test is performed for structural load, to know the optimum element size. Thermal analysis performed to determine temperature mapping, heat flow and overall heat transfer characteristics in a second step. The results are sequentially used as an input in a stress, strain and deformation calculation and to confirm whether geometry of the component meets a particular conductivity requirement. Input values of temperature are collected via experimental testing's observation for analysis. Experimental values of temperature distribution are validated with the result of FEA steady state thermal analysis.

The exhaust manifold is a pipe that conducts the exhaust gases from the combustion chambers to the exhaust pipe. An exhaust manifold is a part of the internal engine that collects the exhaust gases from multiple cylinders into one pipe. Many exhaust manifolds are made from cast iron or nodular iron. Some are made from stainless steel or heavy-gauge steel. The exhaust manifold contains an exhaust port for each exhaust port in the cylinder head, and a flat machined surface on this manifold fits against a matching surface on the exhaust port area in the cylinder head. Some exhaust manifolds have a gasket between the manifold and the cylinder head.

Gaskets are meant to prevent leakage of air/gases between the manifold and cylinder heads. The gaskets are usually made out of copper, asbestos-type material, or paper. In other applications, the machined surface fits directly against the matching surface on the cylinder head. The exhaust passages from each port in the manifold join into a common single passage before they reach the manifold flange. An exhaust pipe is connected to the exhaust manifold flange. On a V-type engine an exhaust manifold is bolted to each cylinder head.

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:

$D_{overall} = \sum Di$ (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 .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.

The primary goal in material selection is not to reach the abnormal oxidization zone under operating conditions. Current documentation is not consistent with regards to the extent of creep damage in exhaust manifold applications. However, other authors define creep deformation as the primary influence on total damage or consider viscous strain either explicitly or implicitly in lifetime evaluation. 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.

A. 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.

B. Understanding Failures

1) TMF Cracking: 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.

2) Leakage: 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.

3) High Cycle Fatigue: 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. 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 overlaying the assembly, temperature and dynamic loading of the system is conducted to calculate the high cycle fatigue safety margin.

III. PROBLEM IDENTITY

In recent years the engine operating temperatures of cars, vans and heavy goods vehicles have been increasing because of environmental legislation on emissions and the need to improve engine efficiency. The motor industry worldwide is highly competitive, operating on small margins and large volumes. Therefore, the profitability is highly geared to reductions in design, development and manufacturing costs. There are very significant economic and environmental benefits from using existing materials. Automobiles have achieved some success with an approach termed here FEA validation (FEAV) for high temperature components. Moving away from a design process which relied primarily on component testing towards a predictive capability based on standardized material data and computer predicted performance of components has resulted in reductions in development costs and timescale. This project describes the analysis process with its various elements with regard to a particular example of an exhaust manifold which has now entered service.

Fig.1. Defects in End connections due to thermal stress

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IV. ANALYSIS METHODOLOGY

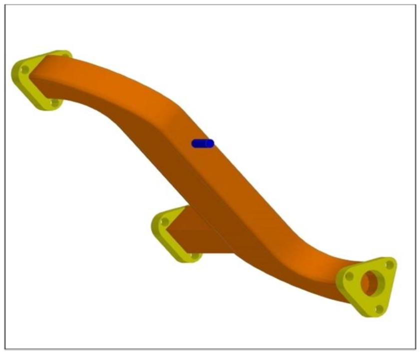

Fig.2. Solid model of the exhaust manifold

Fig.3. Analysis model of the exhaust manifold

A. *Coupled Field Analysis and Results*

The thermal mapping is done by solving steady state thermal analysis of the component by using ANSYS Workbench 14.0. Outer surface of component is exposed to environment (i.e. air flowing in the chamber or the still air around the engine,) on which constant heat transfer coefficient applied with variable ambient temperatures 25°C, 35°C and 50°C. Outer and inner heat transfer coefficient are assumed respectively 30W/m²°C and 70 W/ m²°C, to calculate thermal loads on the exhaust manifold. Thermal analysis is done for thermal mapping on the complete body that will calculate all the nodal thermal values dependent on the thermal resistance of the materials. This temperature mapping is transfer to the structural analysis for calculation of expansion of the structure this will gives the thermal stress and thermal strain results.

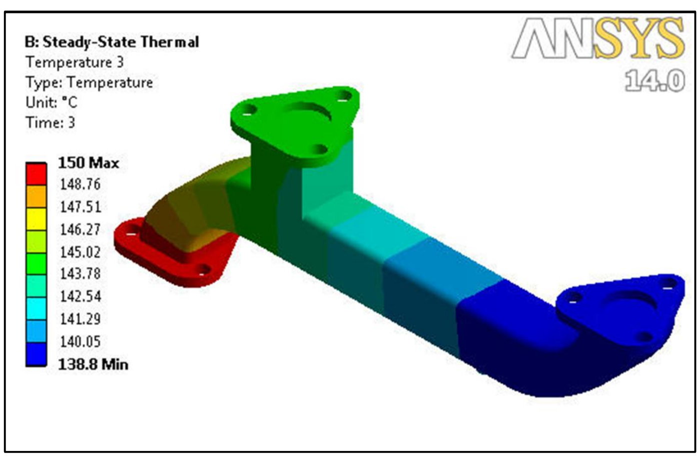

Fig.4. Temperature distribution of cast iron

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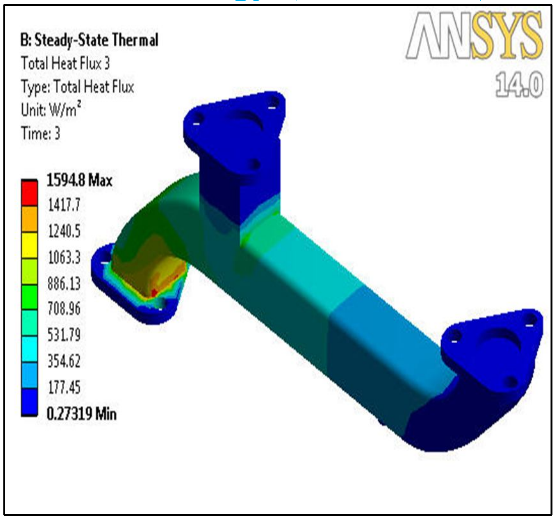

Fig.5. Thermal flux of cast iron

Table.1 Tabulation of thermal analysis and results

Material	Temperature Distribution(°C)	Thermal flux(W/m²)
Cast Iron	138.8	1594.8

Temperature mapping shows that Variation of temperature in the component is depending on the thermal properties of materials used for exhaust manifold analysis. As the boundary conditions are same for both the materials, the maximum temperature region is similar only the variation in temperature gradient exists. The fig.4 & fig.5 also shows that the maximum temperatures around the exhaust manifold pipe area and minimum temperatures are at the mounting flanges attached to the engine wall due to the steady state and comparative high thickness of mounting flanges of exhaust manifold. This means that the evolution of the temperature at every points of the structure must be computed from gas flows inside and outside the manifold. Based on the thermal loading, the analysis aims to compute the stress and strain response of the structure. This temperature load is then transfer to the structure solver by coupling of thermal and structural solver.

B. *Structural Analysis of Cast Iron*

Temperature Mapping Results are transferred to the ANSYS static structural solver for calculation of expansion of the structure this will gives the thermal stress, strain and deformation results.

Table.2 tabulation of structural analysis results

Material	Stress(N/m²)	Deflection
Cast Iron	158.66	0.034

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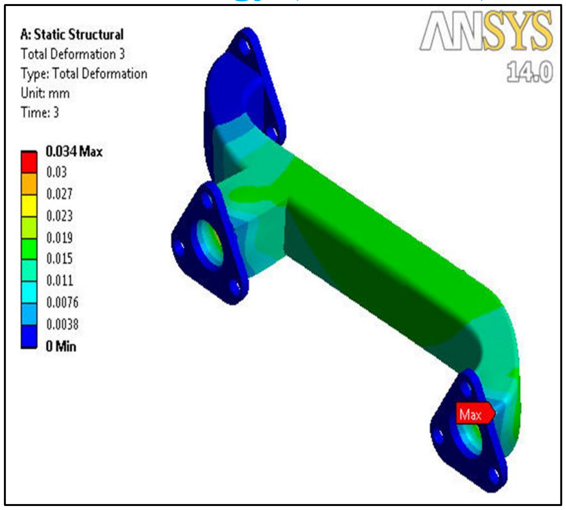

Fig.6. Deflection of cast iron

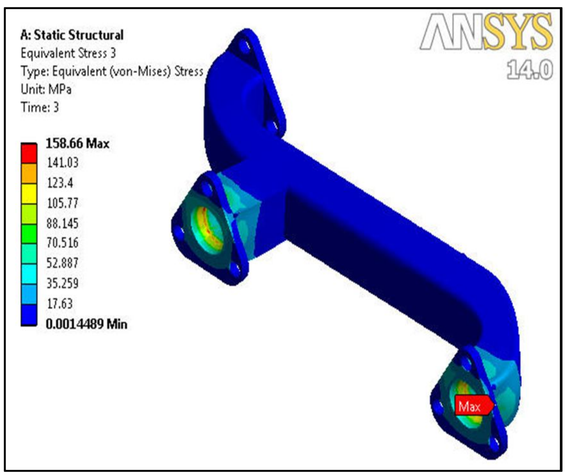

Fig.7. Equivalent stress of cast iron

As one can easily see, the maximum stresses are of the same order of the magnitude as the yield stress. In the cases of Cast Iron (FG 260) the stress concentration and deformation areas remain the same and both are increasing with increasing ambient temperature due to the geometrical shape and boundary condition of the Exhaust Manifold. [Unit - The deformation are given in meter and Stresses are in Mpa]

VI. CONCLUSION

In this project, a methodology to analyze the influence of thermal and structural loadings on an exhaust manifold is developed. The analysis has been performed by using tapered wall exhaust manifold. Solid modeling was developed and analyzed for the boundary conditions. Stress distribution and deflection profiles for both the loads are plotted. ANSYS is being used for this purpose. Linearization across the thickness of the manifold is done to ensure that the stresses developed are well within the yield strength of the material. Finally, to facilitate peak engine performance, an optimum design of a exhaust manifold made of CFRP material was proposed. The results show that it has the capability to withstand high temperatures and pressure.

From this project it is understood that by employing high temperature capability techniques, such as coupled field analysis in ANSYS, it will be possible to derive FEA metrics to allow optimization of engine components to robustly meet the performance requirements at the design stage. Requirement for component testing will also be much reduced. Further the reduction in the time for prototype building and testing reduces the lead-time to market by standardizing the design at the first phase itself.

VII. FUTURE SCOPE

The scope of this project is to re-design an exhaust manifold by determining the thermal stresses and deflections exhibited under various operating conditions with different materials and temperatures. The main objective is to ensure the suitability of the design for a particular material from the view point of reliability and serviceability.

Existing manifolds fails under the operating temperatures and pressure loadings. In this project we develop a design to ensure the best suited design and material for the given operating conditions. Manifold behavior of cast iron can be compared with the metal matrix composites and best suited design can be selected.

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