

Thermo-Mechanical Fatigue Analysis of an Exhaust Manifold

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Abstract: *The exhaust manifold system is an important component of an internal combustion engine, whose primary function is to collect exhaust gases from the cylinder head and direct them to the external environment through the exhaust system. Since the exhaust manifold is directly connected to the cylinder head, it is subjected to high thermal loads generated during the combustion process. In heavy-duty and turbocharged engines, the exhaust gas temperature inside the manifold can reach up to 1000 °C, resulting in severe thermal gradients within the manifold material. The high temperature causes thermal expansion of the manifold, which is partially restricted by the bolted connections at the cylinder head and turbocharger interface. These constraints generate significant thermal stresses and strains in the manifold structure. Repeated heating and cooling cycles during engine operation produce thermo-mechanical fatigue, which may lead to crack initiation and eventual failure of the manifold. In this study, thermo-mechanical analysis of an exhaust manifold is carried out using Finite Element Analysis (FEA) to evaluate temperature distribution, thermal stresses, and fatigue behavior under cyclic loading conditions. The maximum temperature obtained during the thermal cycle is considered as the critical condition for fatigue life estimation. The results of this study help in predicting the durability of the exhaust manifold and improving its design for high-temperature applications..*

Keywords: Exhaust Manifold, OptiStruct, Thermo-Mechanical Analysis, Fatigue, FEA, Thermal Stress

I. INTRODUCTION

The exhaust manifold is a critical component of an internal combustion engine, designed to collect exhaust gases from multiple cylinders and direct them toward the exhaust system and ultimately into the environment. It is typically mounted on the cylinder head and operates under severe thermal conditions. During engine operation, exhaust gases can reach temperatures in the range of approximately 800°C to 1000°C, subjecting the manifold to extreme thermal loading. Due to these high temperatures, the material undergoes thermal expansion.

However, the manifold is constrained by its mounting to the cylinder head and connections to downstream components such as the turbocharger or exhaust pipe. These constraints restrict free expansion and result in the development of thermal stresses and structural deformation (displacement). Repeated thermal cycles during engine operation can further lead to fatigue failure, making thermo-mechanical analysis essential for evaluating the durability and performance of the exhaust manifold.

Therefore, it is necessary to study the thermo-mechanical behavior of the exhaust manifold. In most cases, the highest temperature reached during the thermal cycle is considered for fatigue analysis, because it produces the maximum stress in the manifold. Finite Element Analysis (FEA) is widely used to predict thermal stress, deformation, and fatigue life of engine components. By using FEA, the design can be improved without physical testing, which reduces cost and time. The objective of this work is to perform thermo-mechanical analysis of an exhaust manifold using HyperMesh and OptiStruct and evaluate stress and deformation under operating conditions.



Objective of Project

- To analyze the thermal behavior of the exhaust manifold under high temperature conditions (800–1000°C).
- To evaluate the thermal expansion and resulting deformation (displacement) in the manifold.
- To determine the thermo-mechanical stresses developed due to constrained expansion.
- To identify critical regions prone to high stress and possible failure.
- To study the effect of boundary conditions (bolts, constraints) on stress distribution.
- To perform fatigue analysis under cyclic thermal loading conditions.
- To improve the design and material selection for enhanced durability and performance.

II. LITERATURE SURVEY

Alexandre Schalch Mendes [1] This Paper presents a study of weight reduction in an exhaust manifold of a four cylinders, 3.0 liters Diesel engine. The mass of the entire engine shall be reduced from the current 290kg to 260kg and many components will be redesigned focused on this target. Basically, the wall thickness and flanges of the exhaust manifold will be redesigned and reduced to a value which shall guaranties the component durability. The calculations will be made determining the life cycle of the proposed exhaust manifold, checking if no structural problems can occur. The shape and size of the ducts remain unchanged for performance purposes and no material changes will be considered for the new component.

Taner Gocmez [2] Thermomechanical fatigue (TMF) cracks on exhaust manifolds are often observed for highly loaded engines due to increasing performance and emission demands from the market. Continuously, higher strength materials are searched for, where maximum gas temperatures in some cases are already in excess of 1000 °C. In order to save cost and time, development strategy is built on performing tests on a virtual prototype instead of a physical prototype. The use of advanced simulation technologies enables the design and analyses engineers to identify critical locations in an early phase of development and to meet measures in order to remove local structural weaknesses. During the last decades, several methods are published for the identification phase; considering kinematic and isotropic hardening, creep in material modeling and considering plasticity, creep and oxidation in lifetime modeling.

Cristiana Delprete and Carlo Rosso [3] Thermo-structural behavior of two cast iron commercial exhaust manifolds is investigated through transient nonlinear finite element analysis (FEA). Two different FE models are presented. The first FE model considers interaction between exhaust manifold, gasket and cylinder head. It also considers fasteners initial pretension and geometric constraint conditions. The second FE model only considers the exhaust manifold. Thermal exchange interfaces are evaluated and thermal analyses are conducted to evaluate thermal distribution and to obtain thermal inputs for structural analysis. FE models are solved for stress-strain estimation. Numerical results are validated with experimental data.

Alexandre Schalch Mendes [4] This Paper presents a study of weight reduction in an exhaust manifold of a four cylinders, 3.0 liters Diesel engine. The mass of the entire engine shall be reduced from the current 290kg to 260kg and many components will be redesigned focused on this target. Basically, the wall thickness and flanges of the exhaust manifold will be redesigned and reduced to a value which shall guaranties the component durability. The calculations will be made determining the life cycle of the proposed exhaust manifold, checking if no structural problems can occur. The shape and size of the ducts remain unchanged for performance purposes and no material changes will be considered for the new component.

III. PROBLEM DEFINITION

The exhaust manifold is subjected to severe thermo-mechanical loading due to high-temperature exhaust gases during engine operation. These elevated temperatures induce significant thermal gradients within the manifold, resulting in non-uniform thermal expansion. However, the presence of mechanical constraints such as bolted joints and connections



to the cylinder head restricts free expansion, leading to the development of complex thermal stresses and structural deformation.

For GGG 50 material, the yield strength decreases with increasing temperature, which increases the risk of plastic deformation and thermo-mechanical fatigue failure in critical regions. Stress concentration is typically observed near mounting locations and geometric discontinuities. Therefore, it is essential to perform a coupled thermo-mechanical finite element analysis to evaluate temperature distribution, displacement, and stress fields, and to assess the structural integrity and durability of the exhaust manifold under operating conditions.

IV. METHODOLOGY

4.1 FEA Model :

All others components were modelled with tetrahedral elements as shown in Figure 4.2 model have been modelled as elastic materials. However, the dependency of elasticity modulus on temperature has been considered for materials .The manifold is divided in two parts, in order to accommodate the axial displacements due to material expansion. Manifold & turbocharger modelled as elastic-plastic (Stress-Strain) temperature-dependent material are as shown in Figure 3.3

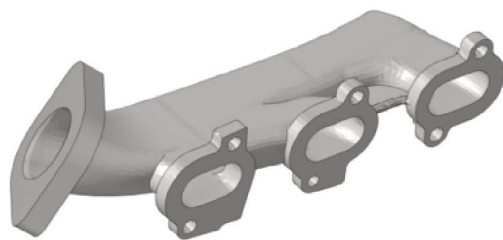


Figure 4.1: CAD Engine Manifold

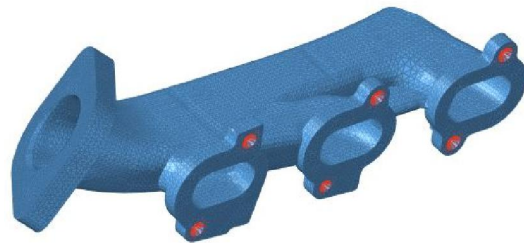


Figure 4.2: FEA Engine Manifold

Meshing of Engine Manifold: For meshing the mesh is generated by keeping mesh size as 5 mm.

4.2 Boundary and Loading Conditions Constraints:

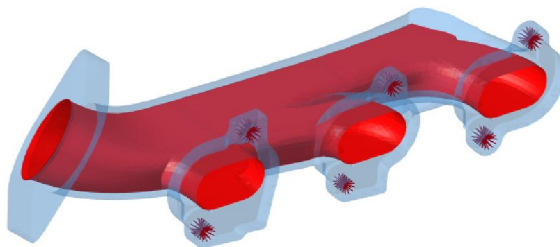


Figure 4.3 Temperature: Inner surface

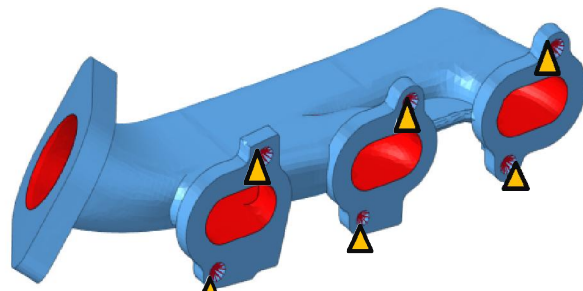


Figure 4.4 Static Load: Inner surface



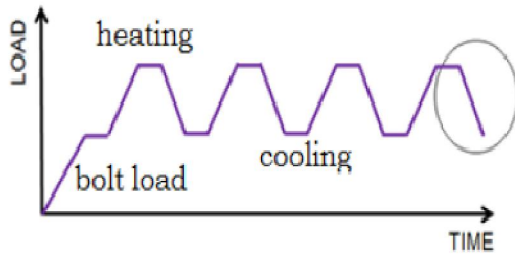


Figure 4.5 Cyclic loading for exhaust system analysis

4.3 Material details:

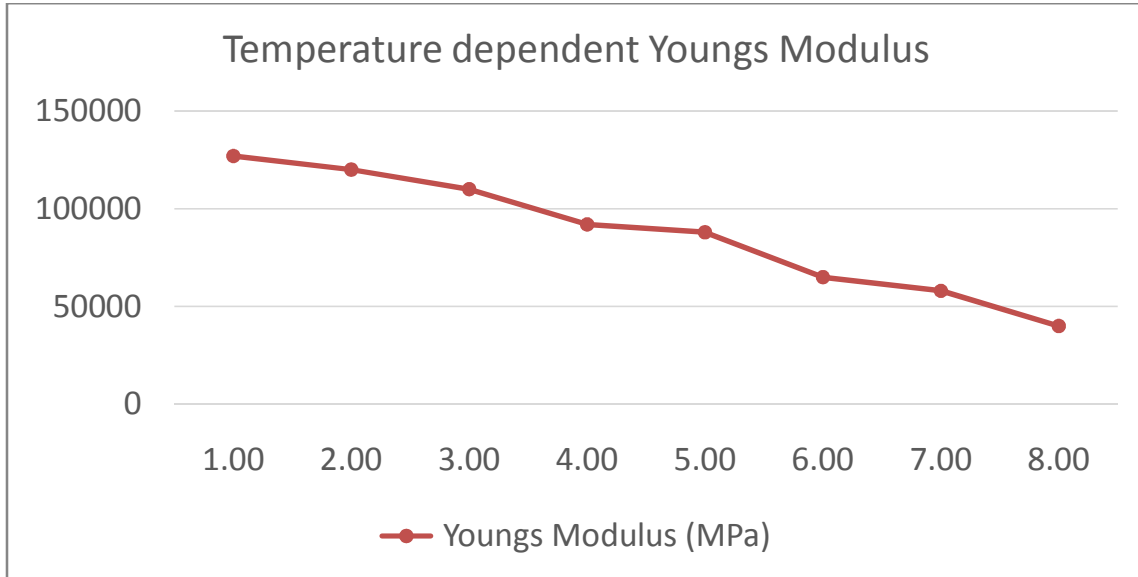
In addition to strength degradation, the Young’s modulus of the material also varies as a function of temperature. At approximately 800°C, the modulus reduces to nearly 20% of its value at room temperature, demonstrating a substantial loss in stiffness. The variation of Young’s modulus with temperature is presented in table no 1 and graph 4.3.1. This reduction in stiffness leads to increased deformation and must be considered in finite element analysis for accurate prediction of structural response.

The representative stress–strain curves of GGG55–SiMo cast iron, as illustrated in table no.2 and graph 4.3.2, indicate a significant reduction in material strength with increasing temperature. Both the yield strength and ultimate tensile strength decrease progressively at elevated temperatures, which directly affects the structural performance of the component under thermo-mechanical loading conditions.

The materials used for the cylinder head and elbow pipe are assumed to operate within the elastic range throughout the analysis. However, the temperature dependency of the elasticity modulus is incorporated to ensure realistic representation of material behavior under high-temperature conditions.

Temperature (Deg C)	Youngs Modulus (MPa)
20	127000
400	120000
538	110000
649	92000
700	88000
760	65000
800	58000
900	40000

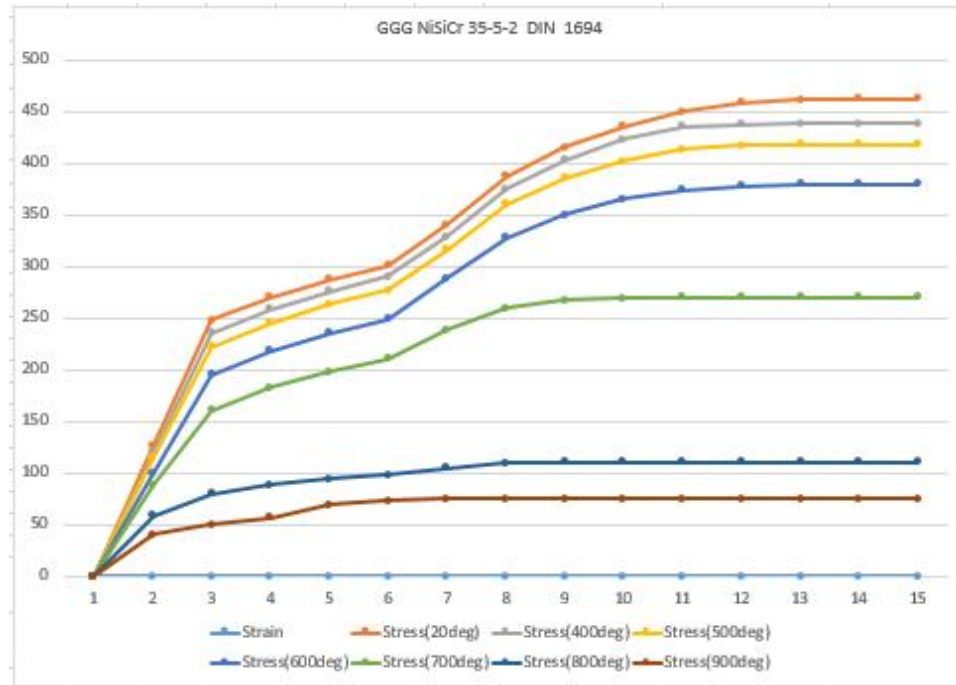




Graph 4.3.1 Elasticity temperature vs modulus

Table 2. Stress Vs Strain material data with different temperature							
GGG NiSiCr 35-5-2 DIN 1694							
Strain	Stress(20deg)	Stress(400deg)	Stress(500deg)	Stress(600deg)	Stress(700deg)	Stress(800deg)	Stress(900deg)
0	0	0	0	0	0	0	0
0.001	127	120	115	100	88	58	40
0.002	248	235	222	195	160	80	50
0.003	270	258	245	218	182	88	56
0.004	287	276	263	235	198	94	69
0.005	301	290	277	249	210	98	73
0.01	340	329	316	288	238	105	75
0.02	387	375	360	328	259	109	75
0.03	415	403	385	350	267	110	75
0.04	435	423	402	365	269	110	75
0.05	450	435	413	374	270	110	75
0.06	459	437	417	378	270	110	75
0.07	461	438	418	380	270	110	75
0.08	462	438	418	380	270	110	75
0.09	462	438	418	380	270	110	75





Graph 4.3.2. Stress Vs Strain material data with different temperature

Table No.3 Mechanical Properties GGG50SiMo	
Youngs Modulus (Mpa)	1.27E+05
Poissons Ratio	0.27
Thermal Conductivity(W/mK)	12
Thermal Expansion Coefficient (ustrain/deg C)	1.18E-05
Desnsity (kg/m3)	7.55E-09

4.4 Thermo Mechanical Analysis and results–

The temperature field obtained from heat transfer analysis .The maximum temperature on exhaust manifold is around 800°C 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





Figure 4.6 Axial displacement of exhaust manifold

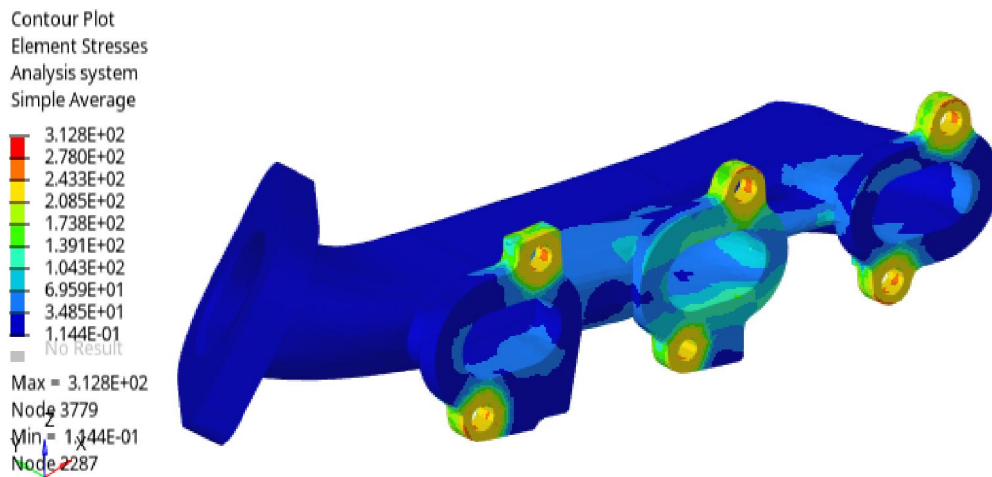


Figure 4.7 Stress of exhaust manifold

Above the minimum cycle is required

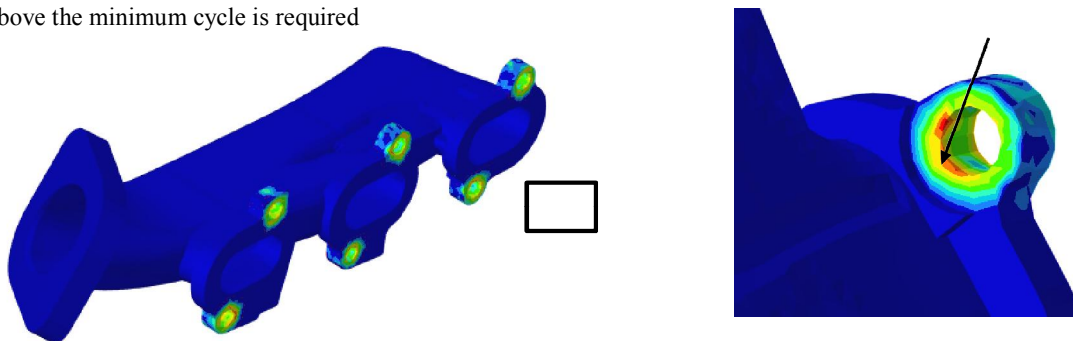


Figure 4.8 Number of cycles for failure on exhaust manifold



The experimental measurement of temperature on the exhaust manifold system was carried out under actual engine operating conditions. During engine running, the manifold is exposed to high-temperature exhaust gases, and therefore, it is important to capture the real temperature distribution for accurate thermo-mechanical analysis.

Thermocouples were used to measure the temperature at different locations on the exhaust manifold. These sensors were placed at critical regions such as near the outlet ports, flange areas, and bolt locations where high thermal gradients are expected. The positioning of thermocouples used for acquiring temperature data at bolt regions is shown in Figure 4.9.

The temperature readings were recorded continuously during engine operation until steady-state conditions were achieved. An intermediate temperature distribution obtained stress from the experimental measurements is presented in Figure 4.7. The results show non-uniform temperature distribution across the manifold, with higher temperatures observed near the exhaust ports and lower temperatures at regions exposed to ambient conditions.

These experimentally measured temperatures were further used as input for finite element analysis to evaluate thermal stresses and deformation. This approach ensures that the simulation closely represents actual working conditions of the exhaust manifold.

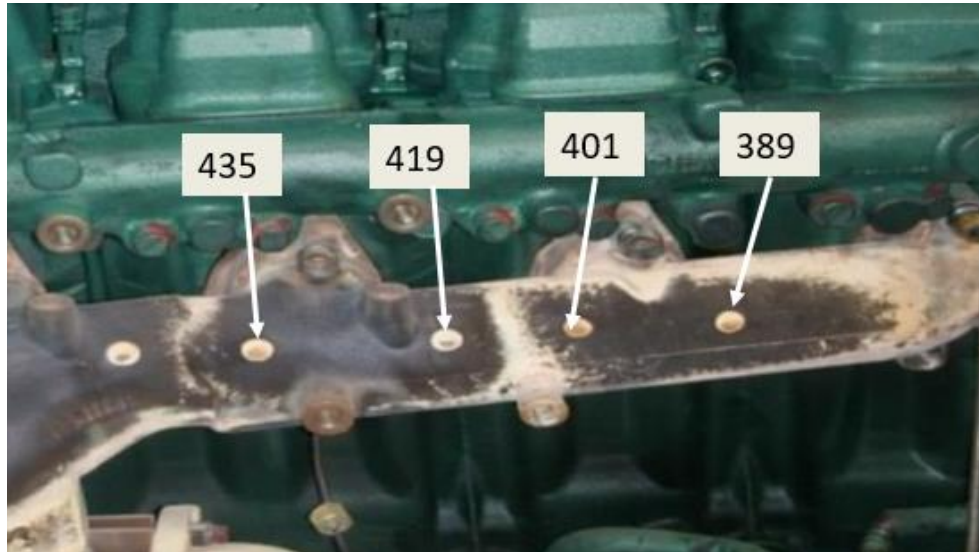


Figure 4.9 temperature measurement on exhaust manifold

V. CONCLUSION

From the thermo-mechanical analysis, it is observed that high temperature causes thermal expansion, which leads to displacement and stress in the exhaust manifold. The maximum stress is found near fixed regions and sharp geometry areas. These regions are more likely to fail. The study shows that both thermal and mechanical effects are important in design. By improving material selection and design, stress can be reduced and the life of the manifold can be increased. This analysis helps in making a safer and more reliable exhaust manifold.

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