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Design and Analysis of an Exhaust Manifold Subjected to Thermo-Mechanical Loading

#1A.U. Kurbet , #2S.Dubey, #3A.R. Kumar, #4S. Razdan

1ashwini.kurbet5@gmail.com
2shashikant.dubey@cummins.com
3arun.r.kumar@cummins.com
4surbhi.razdan@mitpune.edu.in

#14Department of Mechanical Engineering, Savitribai Phule Pune University
Maharashtra Institute of Technology, Kothrud, Pune
#23Cummins India Ltd.
Kothrud, Pune, India

ABSTRACT

The exhaust manifold is mounted on the cylinder head of an engine which collects exhaust gases. It is subjected to thermo-mechanical loading. A finite element (FE) thermo-structural analysis is carried on the manifold and yield margins are calculated. Most of the manifolds yield due to material behaviour at high temperatures. Conventionally linear elastic analysis approach is followed. Linear elastic approach considers linear stress-strain relationship even beyond the yield limit. So the objective is to develop a new approach (elasto-plastic) which is more accurate and captures the actual material behavior beyond the yield limit. Finding the temperature dependent material properties is to be undertaken. Correlation of the yield margins by both the approaches is done. It is observed that the Von Mises stresses are reduced by 57.9% and the yield margins are improved by 58.18% by using the Elastic-Plastic analysis approach.

Keywords- **Exhaust Manifold, Elasto-Plasticity,Thermo-Mechanical Failure, Yield criteria.**

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I. INTRODUCTION

The exhaust manifold is mounted on the cylinder head of an engine collects gases exhausted from an engine, and sends it to a catalyst converter. It plays an important role in the performance of an engine system.The efficiencies of emission and fuel consumption are closely related to the exhaust manifold.It is a simple pipe, which carries the burned gases.Purpose of exhaust manifold is to collect and carry these exhaust gases away from the cylinders with a minimum of back pressure. It is one of the engine components that are expected to endure severe thermal cycling under harsh operating conditions. It is cooled through convection with the cylinder head via thermal contact and natural convection with its surroundings; leading to a large transient thermal gradient.

Exhaust manifold leakage is usually caused by plastic deformation due to the thermal load at the interface between the manifold and adjacent components. The high compressive stresses in the exhaust manifold are caused by the high material temperature and restricted thermal expansion by the screwed connections. When the stress exceeds the yield strength of the material, plastic deformation or strain occurs. We aim to capture this elasto-plastic material behaviour beyond the yield limit in a more accurate way. Accurate material models, thermal and structural boundary conditions, including friction and sliding of the inlet flanges relative to the cylinder head are important in estimating the inelastic strain increment. R. M. Hazime, S. H. Dropps and D. H. Anderson [2],in their work stated that, a transient nonlinear Finite Element Analysis (FEA) method was developed to simulate the inelastic deformation and estimate the thermo-mechanical fatigue life of cast iron and cast steel exhaust manifolds under dynamometer test conditions. Cast high silicon-molybdenum exhaust manifolds are amongst the most widely used in automotive applications due to ease of manufacturing and significant cost savings.

The analysis incorporated appropriate elastic-plastic material models. Transient heat transfer analysisincluded thermal boundary conditions i.e. forced convection of the exhaust gases on the internal surface of the manifold, natural convection on the outside surfaces, and conduction through thermal contact with the cooled cylinder head. Standard ABAQUS built-in material models such as time hardening creep models and isotropic and kinematic hardening plasticity were used for accurate computation of the inelastic strains that the manifold experiences.

Cristiana Delprete and Carlo Rosso[3],in their work described the thermo-structural behaviour of two cast iron commercial exhaust manifolds through transient nonlinear finite element analysis (FEA).Two different finite element (FE) models were presented. The first FE model considered interaction between exhaust manifold, gasket and cylinder head. It also considered fasteners initial pretension and geometric constraint conditions. The second FE model considered only the exhaust manifold. Thermal exchange interfaces were evaluated and thermal analyses was conducted to evaluate thermal distribution and to obtain thermal inputs for structural analysis. FE models were solved for stress-strain estimation. Numerical results were validated with experimental data. Exhaust manifold is cooled by conduction with cylinder head contact and by convection and radiation with the outside environment. The exhaust manifold is affected by thermal exchange concentrated phenomena, rapid transitory and thermal high gradients. Simulation results showed the effectiveness of methodology both for thermal and structural analyses.

NOMENCLATURE

σ : Engineering Stress (MPa)
E : Young’s Modulus (GPa)
ε : Engineering Strain (mm^2)
σ_T : True Stress (MPa)
ε_T : True Strain (mm)
ε_{T_o} : Total Strain (mm)
ε_e : Elastic Strain (mm)
ε_p : Plastic Strain (mm)
T : Temperature (°C)
σ_y : Yield Strength (MPa)
σ_u : Ultimate Strength (MPa)
α : Thermal coefficient of Expansion ($1/°C$)
κ : Thermal Conductivity (W/mK)
h : Convective heat transfer coefficient W/(m^2K)
T_b : Bulk Temperature (°C)
σ_v : Von Mises Stress (MPa)
YR : Yield Ratio

Transient heat transfer analysis correlated well with experimental data. The starting crack locations experimentally observed were well identified by FEA using nonlinear material models.

Guy Lederer, Eric Charkaluk, Laetitia Verger, Andrei Constantinescu [4],stated thatin their work a numerical method for the design of components subjected to severe cyclic thermo-mechanical loading was developed. This tool is based on a Finite Element (FE) analysis. In the first part temperature distribution was obtained and used in the second part for the mechanical computation.

The analyses used the description of the geometry of the part, information of the thermal properties, an appropriate behaviour of the material at low and high temperature and a good assessment of the boundary conditions (heat transfer coefficients, contact). This method was applied to assess the low cycle failure design of a diesel turbo-charged exhaust manifold in cast iron. The calculations, failure location and lifetime estimation, obtained were compared with experimental data. The results showed a good agreement in terms of critical zones location and of lifetime comparison.

Cristiana Delprete, RaffaellaSesana[6].statedthathigh temperature-resistant ductile cast irons behaviour is highly interesting for the manufacture of components, such as exhaust manifolds for automotive applications. In this paper the temperature dependent static, high cycle and low cycle fatigue behaviour of a heat-resistant Si–Mo–Cr ductile cast iron (Fe–2.4C–4.6Si–0.7Mo–1.2Cr) were investigated.

Tensile and high cycle fatigue properties, in terms of elastic modulus, yield stress, elongation at break, fatigue limits, and the stress-life Basquin’s curve parameters were determined at room temperature, 160℃, 500 ℃ and 800 ℃, thus covering the usual temperature range to which actual components, obtained with this kind of material, are subjected. The alloy showed good monotonic properties at low temperature, but showed to be fragile during fatigue tests, due to the high Silicon content in the alloy.

At 500 ℃ mechanical properties are good, with a 40% decrease with respect to 160 ℃ and ductility is increased. The last temperature level of 800 ℃ caused a notice-able drop of the cast iron strength, due to softening and oxidation effects.

I. THERMO-MECHANICAL FAILURE MODES[1]

Thermal failures refer to any failures caused or aggravated by temperature effects such as thermal stress, thermal expansion, and material degradation at high temperatures. Thermo-mechanical failures refer to the combined effects of mechanical and thermal failures. Most engine components experience both mechanical and thermal effects and may be subject to thermo-mechanical failure. Most commonly encountered failures are in the cylinder head, the exhaust manifold, or the piston bowl.

A. *Thermo-Mechanical failure of Exhaust Manifold*

Exhaust manifold leakage is usually caused by plastic deformation due to the thermal load at the interface between the manifold and adjacent components. The high compressive stresses in the exhaust manifold are caused by the high material temperature and restricted thermal expansion by the screwed connections. When the stress exceeds the yield strength of the material, plastic deformation or strain occurs.

After the engine is cooled down, the compressive stress changes to local tensile stress which may exceed the tensile yield strength. The repeated large plastic strain amplitude induced by the cyclic temperature loading results in thermo-mechanical low cycle fatigue (LCF) failure of the manifold. The high metal temperature affects material strength.

B. *Problem Definition*

The exhaust manifold is of a QSK50 Diesel engine. Exhaust manifold is subjected to cyclic loading as per the engine duty cycle. We determine whether the manifold will yield under the worst case condition (i.e. highest temperature at which the manifold operates).Conventionally linear elastic analysis approach is used to determine the yield margins which gives conservative results. Hence we developed a elasto-plastic analysis approach which is more accurate and it captures material behaviour in a more accurate way beyond the yield point. Correlation of both analysis approaches is done for yield margins.Fig.1 shows the geometry of the exhaust manifold which shall be checked for yielding.

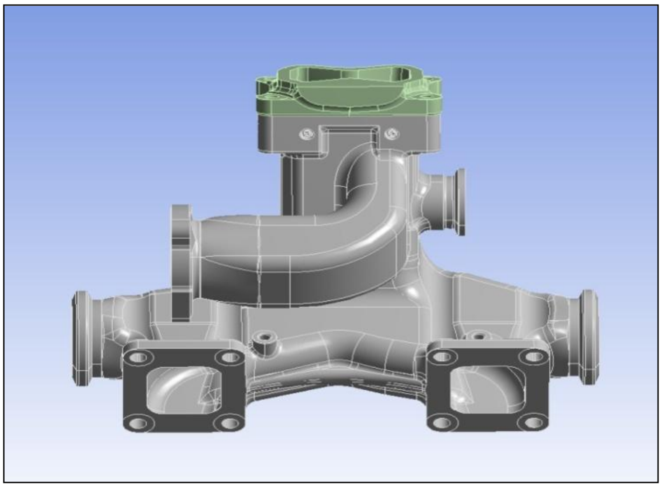

Fig. 1 QSK50 Exhaust Manifold Geometry

II. METHODOLOGY

Designers follow iterative methodology for exhaust manifold design, in which designer makes a design based on his experience and intuition for given operating conditions and other input data.This design is analyzed in finite element analysis (FEA) software by analyst and checked for yield margins. If design is found to be failing then the designer makes modifications accordingly.New design is again checked in FEA software for yielding. This procedure is continued till all constraints are satisfied. Generally such a procedure takes many iterations and hence time, and as an output we get a feasible solution but not an optimal solution. The work is to be completed in two phases as per following plan of action.

A. *Linear Elastic Analysis*

Linear elastic analysis obeys the Hooke's law. It considers linear stress-strain relationship even beyond the yield point. To prepare finite element model of exhaust manifold. The first portion of the investigation will involve carrying out static thermo-structural analysis. The exhaust manifold is subjected to thermo-mechanical loading. It focuses on fully elastic material properties up to the yield point and calculating the yield ratio i.e. von Mises stress to yield strength. Linear elastic analysis approach gives conservative results based on the assumptions considered.

B. *Non-Linear Elasto-Plastic Analysis*

This analysis requires finding temperature dependent material properties. Elasto-Plastic analysis requires temperature dependent true stress-true strain data. We again calculate the yield ratio. Once analysis is done a comprehensive comparison is performed to derive a conclusion on fully elastic versus elastic plastic yield ratio results in FEA.

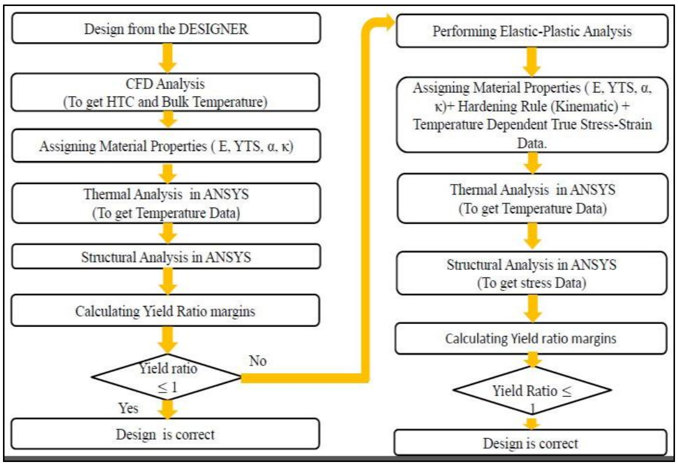

Fig. 2 Methodology Flowchart

III. MATERIAL FOR EXHAUST MANIFOLD[6]

High silicon molybdenum (HiSiMo) ductile cast irons (DCI) are frequently used for high temperature engine components, including exhaust manifolds and turbocharger housings. HiSiMo DCI containing 4-6% silicon with greater than 0.3% molybdenum is characterized by good *high-temperature strength and oxidation resistance.* The temperature range for exhaust manifold is from 20°C to

700°C. The common feature of all ductile cast irons is the roughly spherical shape of the graphite nodules. These nodules act as crack-arresters and make consequently the iron to be more ductile.Mo is known as a strengthening element for ductile cast iron through the formation of carbides. Such carbide formation was reported to increase the tensile strength, thermal fatigue life, and creep resistance.

Table I. CHEMICAL COMPOSITION OF DUCTILE CAST IRON [6]

Element	Composition (%)
C	2.45
Si	4.60
Mn	0.24
P	0.02
S	0.01
Cr	1.18
Mo	0.75
Ni	0.02
Mg	0.04
Cu	003

Table II. MECHANICAL PROPERTIES OFDUCTILE CAST IRON [6]

Material Properties				
Parameters	Values			Units
Temperature	20	160	500	°C
Young's Modulus	0.18	0.1753	0.1437	GPa
Yield Stress	574	550	262	MPa
Ultimate Strength	637.9	625.2	370.5	MPa
Coefficient of Thermal Expansion	$1.28*10^{-5}$	$1.46*10^{-5}$	$1.61*10^{-5}$	1/°C
Thermal Conductivity	33.0	33.3	32.6	W/m°C

IV. ANALYSIS LAYOUT FOR EXHAUST MANIFOLD

The analysis layout includes

C. *Thermo-Structural Linear Elastic Analysis.*

Thermo-Structural analysis includes steady state thermal analysis, whose output i.e. temperature distribution is used as an input for structural analysis. ANSYS 16 is used as the FEA software. It includes the following steps:

1) Finite element modelling of exhaust manifold.
2) Creating contact surfaces between exhaust manifold and turbocharger & Named Sections (i.e. dividing manifold into interfaces namely outer, inner and flange portion)
3) Steady State Thermal Analysis.
4) Steady state Structural Analysis.
5) Yield Ratio.

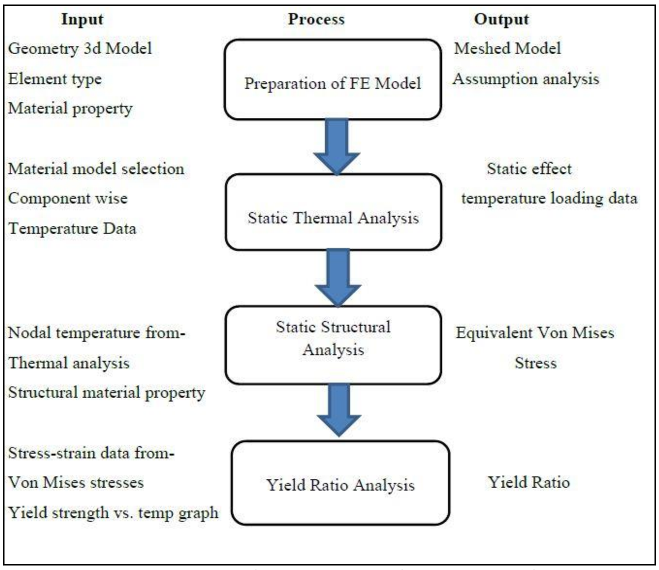

Fig. 3 Work Flow for the analysis of Exhaust Manifold

1) *Finite element modeling of exhaust manifold:* The CAD geometry consists of an exhaust manifold and a dummy turbocharger. Turbocharger is a simple flange with four fasteners. Exhaust manifold and turbocharger is meshed with a 4 node tetra element. Free mesh is used. Solid 87 element type is used for meshing. Meshed model is shown in Fig.4

2) *Contact surfaces & Named Selections:* Contact connections are created between the turbo fasteners and exhaust manifold as shown in Fig.5Exhaust manifold is divided into namely three interfaces i.e. outer section, inner section and flange portion as shown in Fig 6, 7, 8.

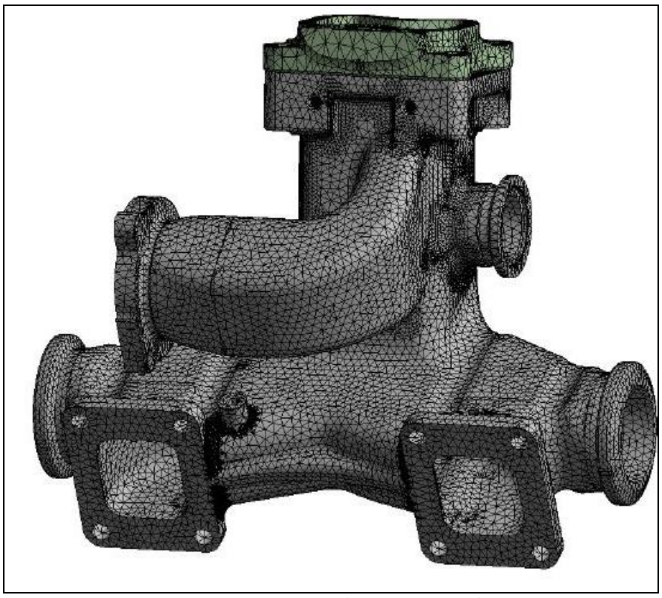

Fig. 4Meshed Model of Exhaust Manifold

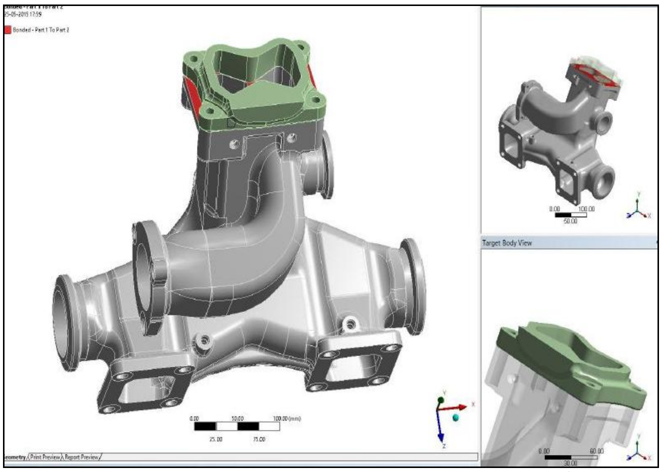

Fig. 5Connections between the turbo and the Exhaust Manifold

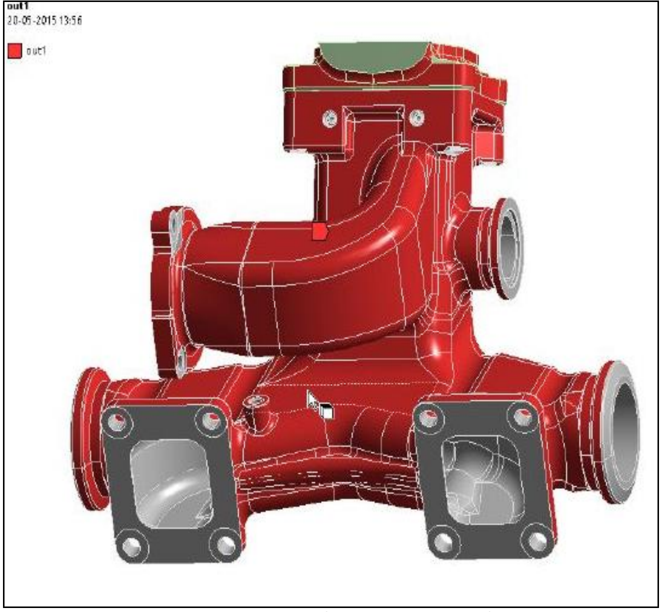

Fig. 6Outer Section of the Exhaust Manifold

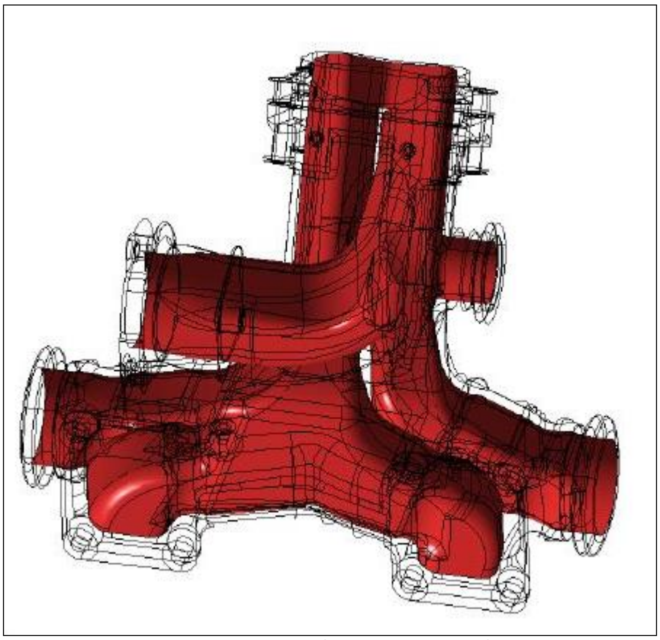

Fig. 7Inner Section of the Exhaust Manifold

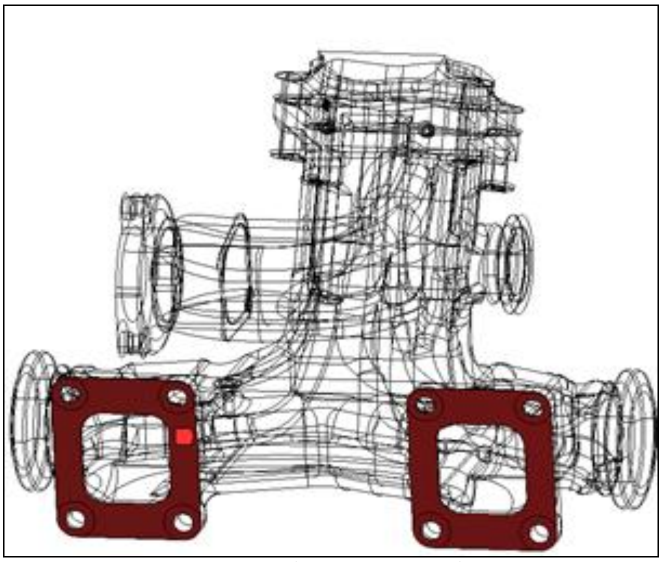

Fig. 8Flange of the Exhaust Manifold

3) *Static Thermal Analysis:* Steady-state thermal analysis determines temperatures, thermal gradients, heat flow rates, and heat fluxes in an object that is caused by thermal loads that do not vary over time. A steady-state thermal analysis calculates the effects of steady thermal loads on a system or component. The thermal properties of most material do vary with temperature, so the analysis usually is nonlinear. We have considered temperature dependent material properties for our analysis.

As exhaust manifold is cooled through convection with the cylinder head via thermal contact and natural convection with its surroundings; leading to a large transient thermal gradient. Convective heat transfer coefficients (h) and bulk temperatures are applied on the respective named sections formed. Output of steady state thermal analysis is the temperature distribution. It indicates the maximum temperature the exhaust manifold has attained.

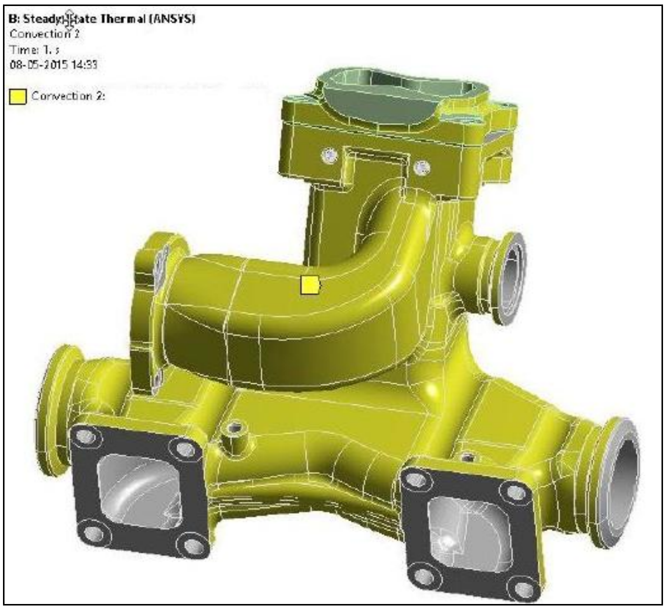

Fig. 9 Convection applied on outer section

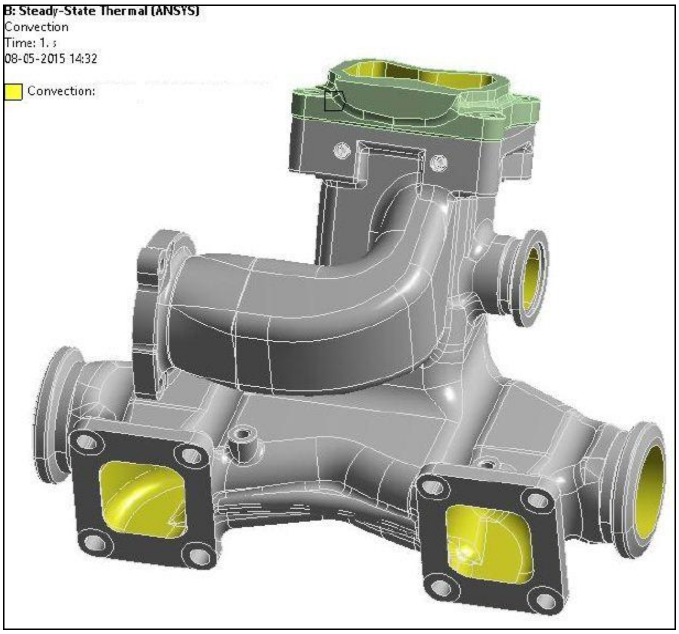

Fig. 10Convection applied on inner section

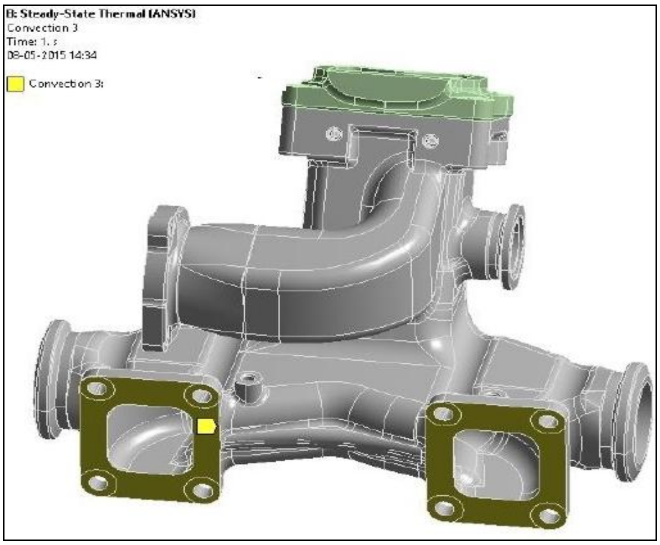

Fig. 11Convection applied on Flange section

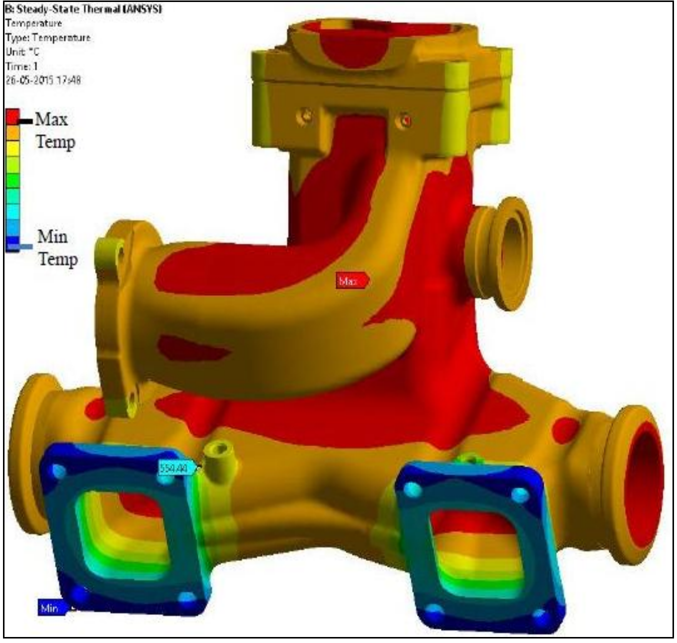

Fig. 12Temperature distribution plot

4) *Static Structural Analysis.* Structural analysis computes stresses and strains that are generated by thermal fields and mechanical loads. The superposition of the temperature fields is computed after the thermal analysis is completed. In actual working configuration, exhaust manifold is fitted on engine cylinder head and it is subjected to mechanical loads created by screw pretension force. The exhaust manifold is made flexible due to existence of play between screws and holes. Exhaust manifold displacements partially balance deformation induced by thermal expansion.

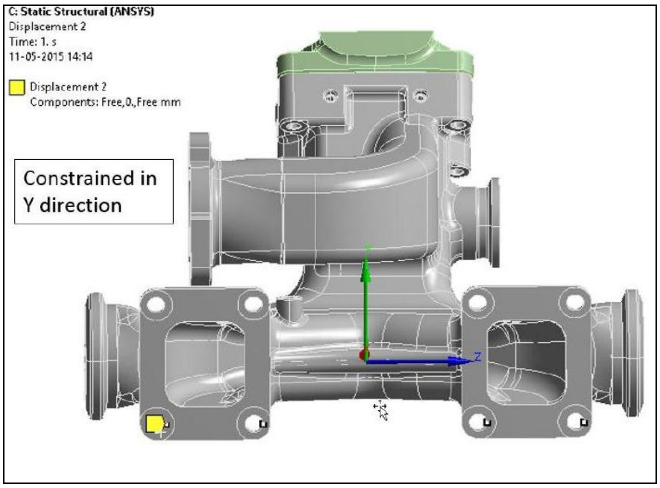

Fig. 13Constraints applied on the bolts in Y direction

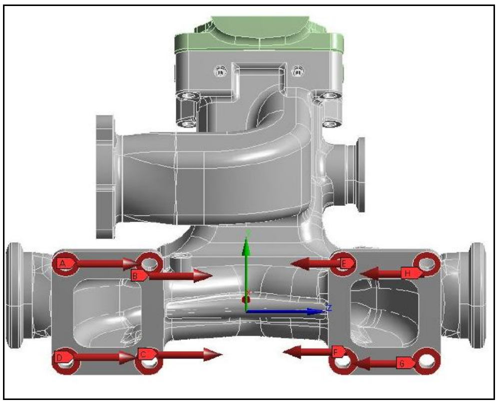

Fig. 14Frictional Forces applied on bolts

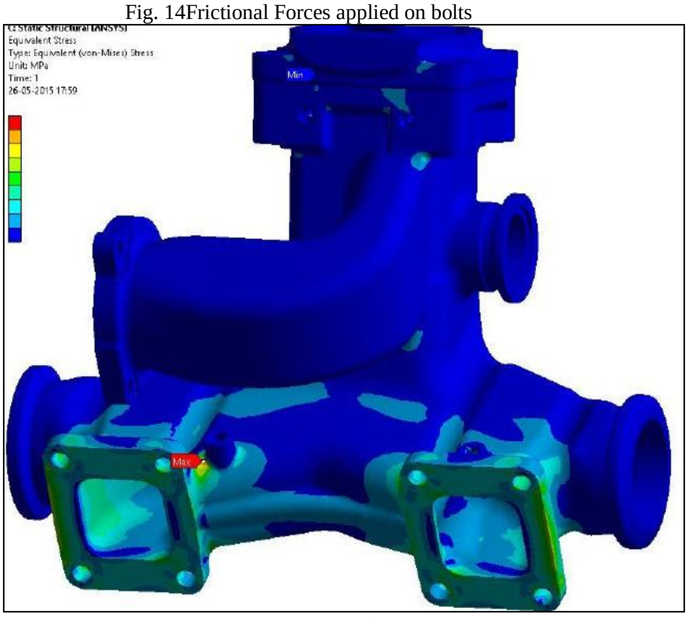

Fig. 15Von Mises Stress Distribution Plot for Linear Elastic Analysis

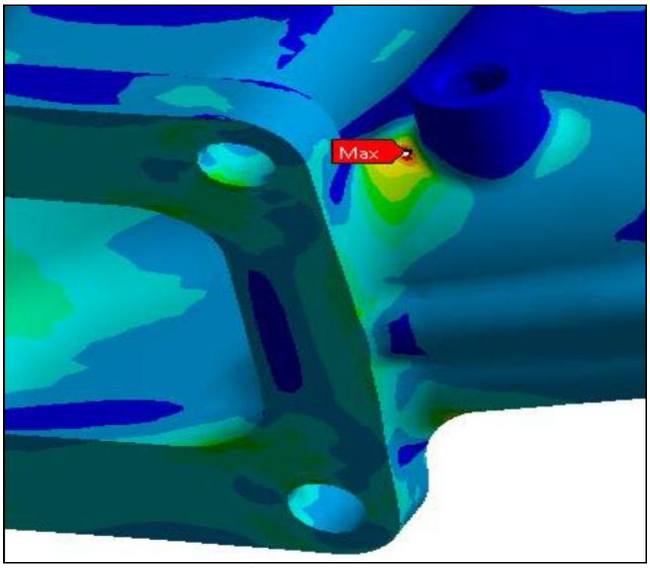

Fig. 16Enlarged View of Von Mises Stress Distribution Plot

5) *Yield Ratio:* The yield ratio is calculated by considering the Von Mises yield criterion. A von Mises yield criterion is formulated in terms of the von Mises stress or equivalent tensile stress, In this case, a material is said to start yielding when its von Mises stress (reaches a critical value known as the yield strength (.As yield strength is a temperature dependent property, it reduces with increase in temperature.

Yield ratio is calculated for all the nodes and the maximum one is considered. If yield ratio (YR)is greater than 1, indicates that the manifold is yielding.

$$\mathit{Yield\ Ratio} \equiv \frac{\mathit{Von\ Mises\ Stress}}{\mathit{Yield\ Strength}} \equiv \frac{\sigma_v}{\sigma_y} \quad (1)$$

This ratio is calculated for all the nodes of the exhaust manifold and the regions where there is high stress concentration are the regions where the manifold has yielded.

In these regions the von Mises stress induced is greater than the yield strength and the particular temperature is noted.

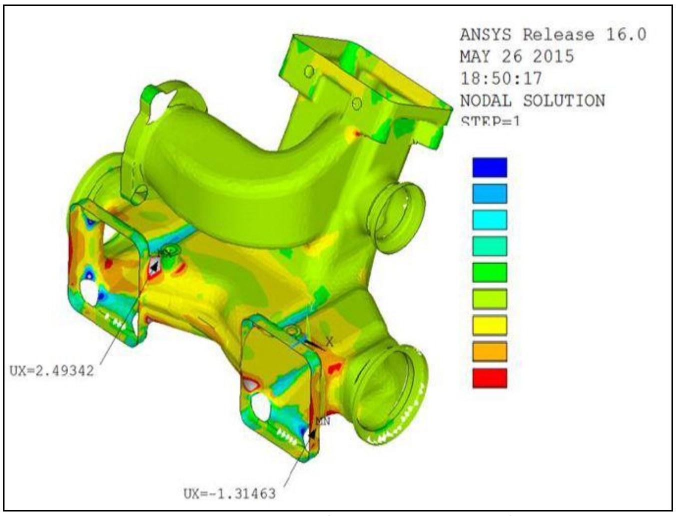

Fig. 17Yield Ratio Distribution plot for the Outer section for linear elastic analysis

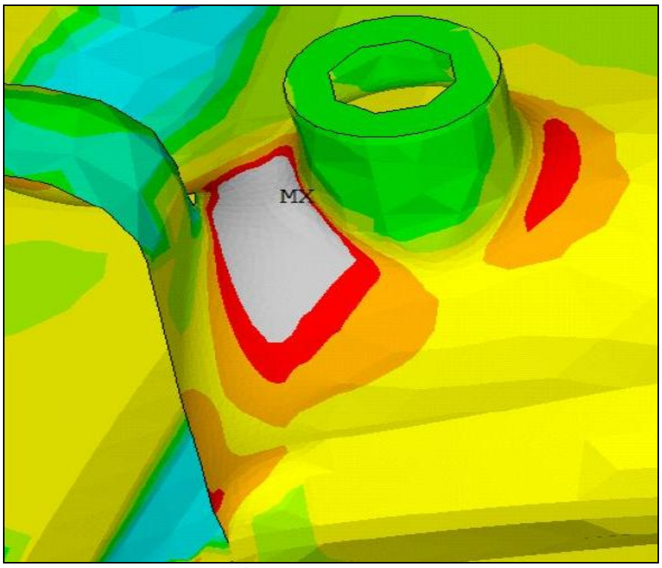

Fig. 18 Enlarged View of Yield Ratio in Stress Concentrated Regions

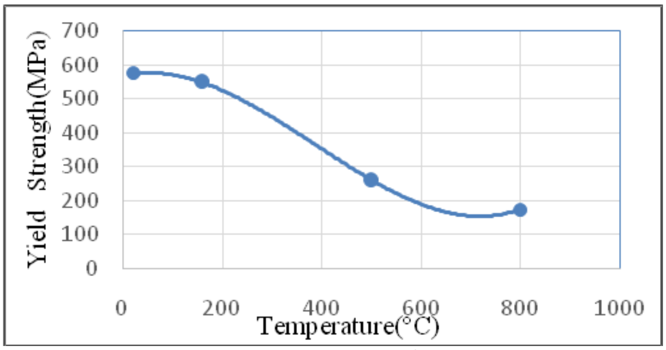

Fig. 19Yield Strength vs. Temperature Plot for Ductile Cast Iron [6]

Table III. YIELD RATIO VALIDATION ANALYTICALLY FOR LINEAR ELASTIC ANALYSIS FOR OUTER SECTION

(Max) Yield Ratio Analytical check (Outer Region)		
Parameters	Values	Units
Temperature	536.37	° C
Von Mises stress	656	MPa
Yield strength at 536.37 ° C	265	MPa
Yield ratio value analytically	2.49	-
Yield Ratio value in analysis	2.4872	-

As seen from Table III, we get the maximum yield ratio for the outer section as 2.49 which is greater than ,hence the manifold yields as the stresses induced are greater than the yield strength of the material.This behaviour of the material after the yield limit is captured well by the elasto-plastic analysis approach.

B. *Thermo-Structural Elasto-Plastic Analysis[12]*

Plastic deformation is defined as permanent change in shape or size of a solid body without fracture resulting from the application of sustained stress beyond the elastic limit. Material nonlinearities occur because of the nonlinear relationship between stress and strain that is; the stress is a nonlinear function of the strain. This type of nonlinearity arises when the material exhibits non-linear stress-strain relationship.

Elastic-plastic analysis uses the modulus of elasticity from the elastic material properties but ANSYS requires yield stress and plastic strains of the material in the plastic range to be manually loaded into the material properties. If the plasticity data is not entered into ANSYS, the stress/strain relationship continues to be linear. This will not provide an accurate result of stress in the plastic range. Material non-linearity is characterized in ANSYS by hardening rules.

1) *Hardening Rules [12]:* This concept describes the mechanism for the growth of the yield surface. It is called the hardening rule. It determines how the yield point changes as a result of accumulation of plastic strain, and depends on the type of material.

In ANSYS there are two hardening models options as Isotropic hardening model and kinematic hardening model. Selection of hardening model in ANSYS affects accuracy of analysis. Hardening model describes the change in yielding due to cyclic loading i.e. yielding of material changes as loading condition changes. During compression yielding reduces or an increase is depending on material behaviour in cyclic loading. But non-linear FE analysis tools require the data to be in the form of “True Stress to True Strain” for FE analysis

2) *Engineering Stress vs. True Stress Strain:* Engineering stress-strain are mostly used for small-strain analyses, while true stress-strain are used for plasticity, as they are more representative measures of the state of the material.The engineering data needs to be converted to true data for use in FE analysis and can be converted using the following formulae:

$$True\ Stress = \ (engineering\ Stress) * (2)$$

$$(1 + \ engineering\ strain)$$

$$True\ Strain = \ ln\,(1 + engineering\ strain)(3)$$

3) *Kinematic Hardening Rule [12]:*Kinematic hardening rule depends on assumption that yield stress in tension is more than yield stress in compression. This will take account of Bauschinger effect. If one loads a specimen beyond the yield stress in uniaxial tension, then unloads and reloads it in uniaxial compression, the new yield stress point in compression is going to be smaller in magnitudethan the original one. This is known as Bauschinger effect. For this analysis work we have cyclic loading, so we have decided to use kinematic hardening rule instead of isotropic hardening rule.

As the manifold is subjected to cyclic loading, we consider kinematic hardening material model. High silicon molybdenum (HiSiMo) ductile cast irons (DCI) is used as the manifold material. Experimental stress-strain curve for the ductile cast iron is converted to true stress-true strain data.

$$True\ Strain = ln(1 + engineering\ strain)$$
$$True\ Stress = (engineering\ stress) * (+engineering\ strain)$$
$$Total\ Strain = Elastic\ strain + Plastic\ strain(3)$$
$$Elastic\ strain = True\ Stress \div Youngs\ Modulus(4)$$

Table IV. KINEMATIC HARDENING INPUT TRUE STRESS VS. PLASTIC STRAIN AT500 [6]

Temperature= 500℃	
Plastic Strain(mm/mm)	Stress(Pa)
0	0
4.32E-05	473.9
0.000110574	912.694
0.000218724	129.247
0.000619368	183.936
0.001529131	218.602
0.002300634	246.165
0.003221942	267.859
0.004638707	292.135
0.006246244	309.366
0.008991421	335.440
0.010629098	340.809
0.012152593	346.157
0.013141221	354.948
0.014535183	351.829
0.016081833	357.224
0.018509598	369.029

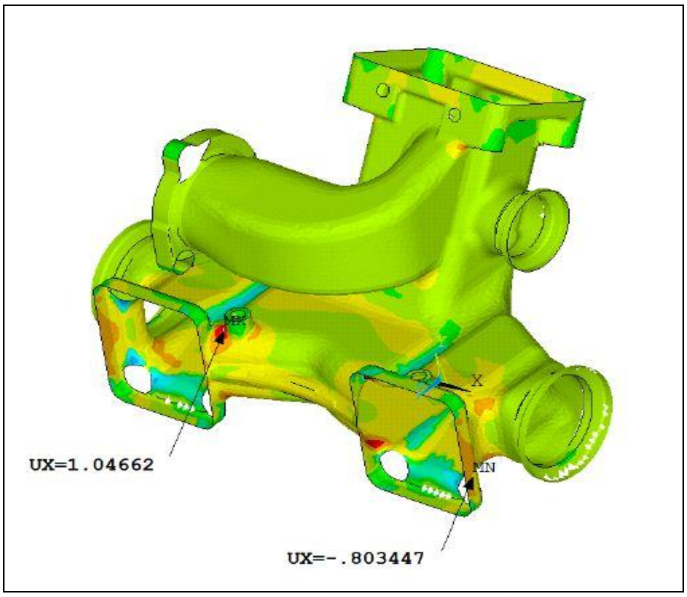

Fig. 20Yield Ratio Distribution plot for the Outer section for Elasto-Plastic Analysis

Table V. YIELD RATIO VALIDATION ANALYTICALLY FOR ELASTO-PLASTIC ANALYSIS FOR OUTER SECTION

(Max) Yield Ratio Analytical check (Outer Region)		
Parameters	Values	Units
Temperature	537.57	℃
Von Mises Stress	276	MPa
Yield strength at 537.57 ° C	264	MPa
Yield ratio value analytically	1.05	-
Yield ratio value in analysis	1.046	-

V. RESULTS

The von Mises stresses induced in the exhaust manifold in both types of analysis approaches are shown if Fig.21.

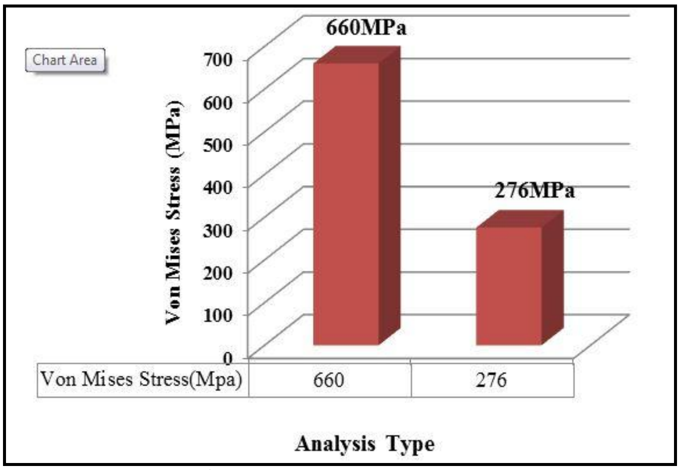

Fig.21 Correlation of Von Mises Stresses in both analysis approaches

The percentage reduction in von Mises Stresses in linear elastic and elasto-plastic analysis approach is given in Table VI.

Table VI. VONMISESSTRESS REDUCTIONFOR OUTER SECTION

Correlation of Von Mises Stresses Type of Analysis			
Parameter	Units	Linear-Elastic	Elasto-Plastic
Node Number	-	79477	79477
Von Mises Stress (Mpa)	MPa	656	276
% Improved Margins	-	$\equiv \frac{(656-276)}{(656)} \times 100 \equiv 57.9\%$	

The yield ratio values in the exhaust manifold for outer section in both types of analysis approaches are shown if Fig.22.

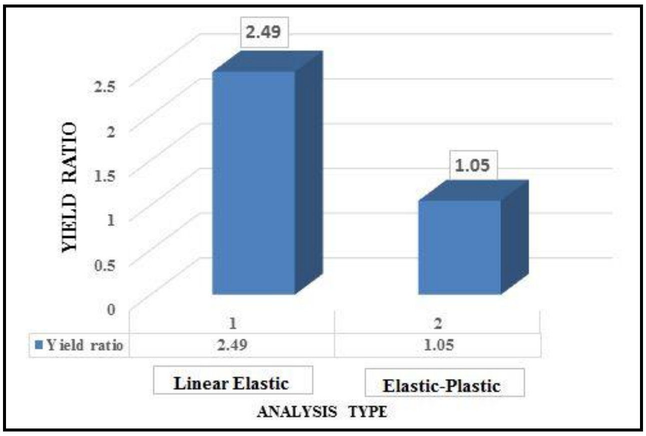

Fig. 22 Correlation between Yield Ratio Margins by both linear and Non-linear analysis for the same node for outer named section.

The percentage reduction in yield ratio values in linear Elastic and elasto-plastic analysis approach is given in Table VII. The yield margins are improved by 57.8%.

Table VII. YIELD RATIO REDUCTION FOR OUTER SECTION

Correlation of Yield Ratio by Type of Analysis		
Parameter	Linear-Elastic	Elasto-Plastic
Node Number	79477	79477
Yield Ratio	2.49	1.05
% Improved Margins	$\equiv \frac{(2.49-1.05)}{(2.49)} \times 100 \equiv 57.8\%$	

VI. CONCLUSIONS

- Using Von Mises yield criterion it is concluded that as the maximum equivalent stresses induced in the manifold are greater than the yield strength of the material the material has plastically deformed.
- New procedure for exhaust manifold design using elasto-plastic analysis is developed and validated showing good amount of improvements in equivalent Von Mises stress gradient and the yield margins, satisfying the main objective of the research.
- Elasto–plastic analysisprocedure which requires temperature dependent true stress – true strain data and a hardening rule which is calculated using the engineering stress-strain temperature dependent data.
- It is concluded that von Mises stresses have reduced by 57.9%. This is because linear elastic approach obeys the Hooke’s law i.e. stress is directly proportional to strain even beyond the yield limit of the material. Linear Elastic analysis doesn’t consider temperature dependent non -linear material behavior.
- Elasto-plastic analysis approach considers temperature dependent material behavior and a use of hardening rule. As exhaust manifold is subjected to cyclic loading as per the engine duty cycle.Hence Kinematic hardening is used as a hardening rule.
- Yield margins are defined as ratio of Von Mises stresses to yield strength of the material.As stresses have reduced using elasto-plastic approach ,Yield ratio is improved by 57.8%

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