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Thermo-Mechanical analysis of composite exhaust manifold

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Abstract — *The main objective of this research work is to suggest a suitable material for exhaust manifold which will be light in weight and have better thermal properties as compared to cast iron, which is presently used. Exhaust manifolds are subjected to high thermal cycles ranging from 500°C to 800 °C and pressure ranging from 100 to 500 KPa. For this reason, high temperature application composites such as ceramics and thermosets were studied. Accordingly, Carbon Epoxy, S-glass Epoxy and E glass epoxy were shortlisted. Thermal and static structural analysis using shortlisted material and cast iron was done on single cylinder engine and four-cylinder engine exhaust manifold using Ansys 16. For all materials heat flux and thermal stresses are calculated. It is found that the results of theoretical calculations are in the range of the results obtained by Ansys 16.*

Keywords*-Exhaust manifold, composite materials, 3D modelling, Thermo-mechanical Analysis, Ansys*

I. INTRODUCTION

Exhaust system is an assembly of various components that takes care of the burnt gases produced by an engine of a vehicle. The various components that make an exhaust system are an exhaust manifold, a catalytic converter and a muffler. Exhaust manifold collects the exhaust gases from multiple cylinders into one pipe and supplies it to catalytic converter, muffler and then to atmosphere.

The temperature of exhaust gases in the exhaust manifold reaches as high as 800° C. The exhaust manifold is affected by thermal stresses and deformation due to temperature distribution. Cracks and leaks are major problems in exhaust manifolds. Exposure to the normal heat cycles of an engine can cause cracks in an exhaust manifold. As the vehicle continues to age, the cracks turn into holes.

Figure 1. Worn-out exhaust manifold

The main culprit for manifold damage or wear is rust and it can cause a multitude of problems. This problem affects cars that are normally used for short distance journeys; as the exhaust system never reaches the proper temperature to completely evaporate the water that has accumulated inside the exhaust manifold due to the condensation process.

Manifolds are often made of cast iron in stock production cars, and may have material-saving design features such as to use the least metal, to occupy the least space necessary, or have the lowest production cost. These design restrictions often result in a design that is cost effective but that does not do the most efficient job of venting the gases from the engine. To overcome these drawbacks a material has to be used which will be light in weight, has good temperature strength, less thermal conductivity in radial direction and also should be durable and economical.

II. LITERATURE SURVEY

Yang Yun Hong, Cao Zhan-Yi, Lianzhen Song & Yu Hai Xia [11]: The aim of this paper is to find a new material composition for exhaust manifold in first automotive works (FAV) to meet reduced pollutant emission and high efficiency. The repeated heating/cooling test was performed under cyclic heating at various maximum heating temperature (T_{max}) ranging from 800^0 C to 900^0 C and minimum temperature of 200^0 C was maintained. 4.7% Si - 1.1% Mo Nodular Cast Iron was used as a specimen. Thermal fatigue cracking behaviour was inspected by use of optical microscope, scanning electron microscope and energy dispersive spectroscope. It was found that cracking always initiates at the bigger surface of specimen and showed cross shape budding. The reasonable working temperature of high SiMo Nodular Cast Iron is not more than 840^0 C.

M. Ekstrom & S. Jonsson [12]: The aim of this paper is to create guidelines for material selection at different temperature. High temperature tensile testing, Low cycle fatigue testing (LCF), Thermal diffusivity and many other physical properties were tested. The ferritic alloys SiMo51 and 1.4509 show the most favourable properties having high thermal conductivity and low thermal expansion. The SN curves shows that up to high temperature (800 $^{\circ}$C) HK30 has highest fatigue life. SiMo51 showed good mechanical properties up to 500°C. Austenitic steels are superior only at higher temperature.

Dr. L. Suresh Kumar [5]: This paper showcases the various factors to be considered while designing an optimal engine to satisfy the increasing performance demand and to reduce the weight. It was observed from design consideration that engine power could be maximized at high speed if gases can be lead from piston chamber to exhaust manifold smoothly and heat radiation into surrounding can be reduced by coating exhaust header with ceramics. FEA consideration show that if stresses and deflections obtained in various analyses are under the design limit of the material used then the design can be considered as a safe.

Agilesh.A & P. Pichandi [3]: The aim of this paper was to redesign the exhaust manifold in order to increase reliability and serviceability to meet the new emission norms by examining cast iron. CAD/CAM software CREO 3.0 and ANSYS 14.0 were used for modelling and analysis. FEM analysis was done using tetrahedral element of 1st order and convergence test was performed for structural load. The influence of increase thermal and structural loadings on exhaust manifold lead to design of tapered wall exhaust manifold. Linear thickness of manifold resulted in stresses within the yield strength of material. Also, to ensure peak engine performance sustaining high pressure and temperature CFRP material was proposed.

Aakash Mutkule, Akshay Satpute, Shubham Koshatwar & Saurabh Dharmadhikari [7]: This paper deals with analysis of exhaust manifold of different material under similar working condition. In this paper, they have designed the exhaust manifold by using CREO parametric. Thermal, Structural and Modal analysis of the design for gray cast iron, ferritic stainless steel and titanium is done on ANSYS 14.0 and then the results are compared. It is observed that of all three, the results for titanium are better.

Gopaal, M.M.M Kumara Varma & Dr. L. Suresh Kumar [4]: The paper "Thermal & Structural Analysis of an Exhaust Manifold of Multi-Cylinder Engine" deals with thermal and structural analysis of a multi-cylinder exhaust manifold made of cast iron, for given dimensions. 3D model is prepared on NX-CAD software using the dimensions from the drawing. Thermal and coupled-field analysis along with harmonic analysis is done on finite element analysis software ANSYS. The temperature distribution is found and results obtained show that von-misses stress generate is 115MPa which is less than yield strength of cast iron (130MPa), also 6 natural frequencies for structure are identified, the von-misses stresses at 1250, 1300, 1450 Hz are equal to the yield strength of cast iron. The purpose of this analysis was to ensure the safety of the defined design of the exhaust manifold.

Ashwani Kumar, Arum Kumar, Arpit Dwivedi and Pravin Patil [6]: In this paper research work on design and analysis of 4-stroke 4-cylinder exhaust manifold using 321-austenitic stainless steel is done. Thermal, Static structural and Modal analysis is performed using ANSYS software to check high temperature strength and modal natural frequencies, while the structure of exhaust manifold was modelled using SOLIDEDGE software. It is observed that thermo-mechanical fatigue is the main reason for exhaust manifold failure. The 321-austenitic stainless-steel exhaust manifold maintains its properties at higher temperatures (800°C). The natural frequencies of the exhaust manifold for the first five orders were obtained along with its vibration mode.

Dr. Magali Rollin & Christophe Buchler [10]: The purpose of this paper was to present a class of glass-ceramic matrix composites which could withstand 300-1000ºC temperature range while being affordable to use. These composites are designed and processed with the same techniques and tools as conventional CFRP. A glassy phase containing silicon oxide Nano- particles, which are inherently resistant to heat and fire, is specifically featured in the glass-ceramic matrix composites which are reinforced with continuous silicon carbide fibres according to level of material performance. It was tested in laboratory and practically in heat shields and exhaust components. The results showed that this composite can successfully resist temperatures up to 1000ºC, also due to its low CTE thermal fatigue was not an issue and 65% weight reduction can be achieved when transitioning from metals to this composite. Properties of glass-ceramic matrix composite are specified:

Table 1. Properties of Glass Ceramic Matrix Composite

Property	Value
Density	1.8 to 2.2 g/cm^3
Coefficient of thermal expansion	3×10^{-6} /K
Thermal conductivity (through thickness)	0.90 W/m.K
Thermal conductivity(in-plane)	0.95 W/m.K

Sathishkumar T.P & Naveen J [9]: This paper deals with the study of glass fibres reinforced polymer composites prepared by various manufacturing techniques. The properties of composites depend on the fibres laid or laminated in the matrix during the composites preparation. Soy bean oil based polyurethanes of E-glass reinforced composite have better thermal stability than petrochemical polyol jeffol based polyurethane. Increased glass fibres content in composite delays the thermo-oxidative decomposition in chopped strand mat E-glass fibres. E-glass fibres waste polyester compound without filler showed that degradation temperature shifted from 209.8°C to 448.7°C and mass loss shifted from 1.8 wt% to 4.4wt%.

Jean Luc Battaglia & Abdelhak Saci [8]: This paper focuses on thermal conductivity measurement of 3 composites constituted from same epoxy resin (5052-4 RTH BMI) and different carbon fibres namely XN15, YSH70 and CN90, having 40 folds of R=1.5cm and thickness 3mm cylinder. The process lead to orientation of fibres in [-45°, 0°, 45°, 90°]. The hyphen plane K_1 and transverse K_2 thermal conductivity are measured at 77K and 300K using hot disk technique results are as follows:

Table 2. Thermal Conductivity of Composite Materials

Composite	T^0(K)	$K_1(Wm^{-1}K^{-1})$	K_2 $(Wm^{-1}K^{-1})$	$R_c(m^2KW^{-1})$
XN15/Epoxy	37	0.479±0.057	0.203± 0.005	$\{5.231\pm0.21\}\times10^{-4}$
	300	1.794±0.030	0.886± 0.004	$\{4.409\pm4.409)\times10^{-4}$
YSH10/Epoxy	77	28.02± 0.25	0.168± 0.02	$\{1.4\pm0.1\}\times10^{-4}$
	300	152.78± 0.9	0.456± 0.02	$\{3.699\pm0.3\}\times10^{-4}$
CN90/Epoxy	77	49.85± 0.91	0.324± 0.035	$\{4.032\pm0.1\}\times10^{-4}$
	300	230.22± 1.20	0.602± 0.03	$\{4.429\pm0.2\}\times10^{-4}$

Sweta Jain & AlkaBani Agrawal [13]: This paper deals with the study of thermal stresses and deformation on different materials of exhaust manifold under conditions close to real life situation for an off-road vehicle diesel engine. The different materials taken in consideration are cast iron (FG260) and structural steel. FEA analysis is done on ANSYS WORKBENCH 14.0 to calculate steady state temperature distribution by performing thermal analysis. Structural analysis is done to find deformation, stress and strain by taking inputs from thermal analysis. Flanges are kept practically fixed and the ambient temperature are considered as 25°C, 30°C, 50°C by covering natural to highest ambient temperature. From the investigation performed it can be concluded that critical area of thermal stress concentration and deformation for both material is almost same.

III. METHODOLOGY

The objective of the project was decided by taking into consideration various shortcomings in the material of the exhaust manifold and also problems due to leakages affecting other parts of the engine. The first step to be taken after deciding our objective was to locate a feasible type of a car engine and a bike engine. This was done by taking into account the cost of the manifold and the availability of engine. Accordingly, 100cc single cylinder bike engine and 1248cc four-cylinder inline engine has been considered. The next step was to get the dimensions of these engines which was done by reverse engineering.

On the basis of the thorough research done during the literature survey of around 11 papers the boundary conditions on the system are defined. After measuring the dimensions of exhaust manifold a 3-D model of both the manifolds were created on SOLIDWORKS workbench. After the study of composite material, based on the application, availability and cost, few composite materials were shortlisted on the basis of thermal and mechanical properties which were Carbon fiber, E-glass epoxy and S-glass epoxy.

Theoretical calculation to find various factors like heat loss, surface area of exhaust pipe, heat flux and thermal stresses was done according to heat transfer equations [12] [13]. Simulation of the design using cast iron (material currently used) and the short listed composite materials was done by using finite element analysis software ANSYS 16.0. The results indicating thermal stresses were noted and compared with the theoretical calculations. The simulation results were compared on the basis of above factors and a better composite material is shown in the results and accordingly, that composite material has been proposed in the conclusion.

IV. DESIGNING OF EXHAUST MANIFOLD

Here we have selected 2 vehicles engine, a 2-wheeler Hero Honda Splendor and a 4-wheeler Hyundai i10 detailed specifications for which are as follows

Table 3. Details of Splendor engine

Model:	Hero Splendor
Engine Capacity:	100cc
Torque:	8 N-m
Power:	8.2 bhp
Type of Cylinder:	Four-Stroke Single Cylinder
Mileage:	70 Kmpl
Cylinder Bore Dia.:	50 mm
Piston Stroke Length:	49.5 mm
Indicated Power:	6.97 hp

Figure 2. Engine and Exhaust manifold

Table 4. Details of Hyundai i-10 engine

Model:	Hyundai i10
Engine Capacity:	1248cc
Torque:	118 N-m
Power:	78 bhp
Type of Cylinder:	Four-Stroke Single Cylinder
Mileage:	20 Kmpl
Cylinder Bore Dia.:	71 mm
Piston Stroke Length:	78.5 mm
Indicated Power:	66.3 hp

Figure 3. Hyundai i-10 engine and exhaust manifold

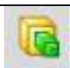
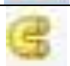
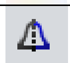
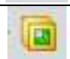
The dimensions for exhaust manifolds of both the engines are recorded with reverse engineering. Then with the help of SOLIDWORKS the 3D models are created for both the exhaust manifolds.

4.1. SOLIDWORKS

Solidworks is a solid modelling CAD and CAE Dassault Systems computer program that preferably works on Microsoft windows. It is a solid modeller that makes use of parametric feature-based approach for creating models and assemblies. Basically, designing on Solidworks starts with 2D views simultaneously generating 3D design. It is purely a product that is used to design machines. Solidworks is more user friendly than any other 3D modelling program with respect to the terms of solid modelling, editing of designs, creation of mechanism, etc. System requirements for solidworks are:

I. Microsoft Windows 7/8/8.1/10 Operating System
II. RAM: 4GB minimum
III. Space: 64GB minimum

Table 5. Table Representing Command, Icon andit's Description in SOLIDWORKS.

Sr. No.	**Command**	**Icon**	**Description**
1.	Extrude		To give specific thickness to a 2D drawing.
2.	Sweep		To create a solid geometry along a specified path.
3.	Mirror		To mirror an entity about a specified axis.
4.	Extrude cut		To eliminate the excess 3d geometry up to a specified length.
5.	Intersect		Intersect two 3D geometry.

Using these commands 3D model of exhaust manifold can be made. The model is shown bellow. This model is imported in Ansys for Thermal analysis.

Figure 4. Exhaust manifold of Hyundai i-10 engine

V. THEORETICAL CALCULATIONS

Let us consider an exhaust manifold to be a straight pipe of uniform cross section. The calculations performed are based on Fourier's law of heat transfer.
The working conditions are as follows:
Flue Gases Temperature (T_2): 500^0C
Heat Transfer Coefficient of Flue Gases (h_2): $70W/m^2K$
Ambient Air Temperature (T_1): 30^0C
Heat Transfer Coefficient of Ambient Air (h_1): $25W/m^2K$

Table 6. Dimensions of exhaust manifold

Dimensions	Single cylinder engine exhaust manifold (mm)	Four- cylinder engine exhaust manifold (mm)
Total Length (L):	440	270
Outer Radius (r_2):	15	34
Inner Radius (r_1):	13.5	30

Following formulae are used to evaluate heat flux and thermal stresses induced in different materials.

Heat loss from a pipe [1],

$$Q = \frac{2\pi L(T_2 - T_1)}{\frac{1}{r_1 \times h_2} + \frac{ln\frac{r_2}{r_1}}{K} + \frac{1}{r_2 \times h_1}}$$

Area for the heat flow through a hollow cylinder [1],

$$A = \frac{2\pi L(r_2 - r_1)}{ln\frac{r_2}{r_1}}$$

Heat Flux [1],

$$q = \frac{Q}{A}$$

Thermal Stress[2],

$$\sigma = E \quad \alpha \quad \Delta T$$

where, E = young's modulus
α = coefficient of thermal expansion
ΔT = temperature gradient

Following are the thermal properties of different materials:

Table 7. Thermal properties of materials

Material	Thermal Conductivity (W/mK)	Young's Modulus(E) (GPa)	Yield Strength (MPa)	Thermal Expansion Coefficient (10^{-6}/K)
Carbon Fibre[16] [17]	24	228	3500	-1 to 8
S-Glass Epoxy [15]	1.3	90	5000	2.9
E-Glass Epoxy [14]	1.27	78.5	2800	5
CI(ASTM)A-48	46	100	130	11

Put these values of thermal properties and dimensions of exhaust manifold in the formulae, we found following results

Table 8. Results for single cylinder engine exhaust manifold by Theoretical Calculations

Material	Heat Flux (W/m^2)	Thermal Stress (MPa)
Grey Cast Iron	8863.1	161.17
S-Glass Epoxy	8862.3	31.81
Carbon Fibre	8862.12	61.93
E-Glass Epoxy	8862.5	57.93

Table 9. Results for four-cylinder engine exhaust manifold by Theoretical Calculations

Material	Heat Flux (W/m^2)	Thermal Stress (MPa)
Grey Cast Iron	8898.67	154.146
S-Glass Epoxy	8896.35	34.43
Carbon Fibre	8896.8	62
E-Glass Epoxy	8896.1	58.38

VI. FINITE ELEMENT ANALYSIS

6.1. Introduction to FEA:

Finite element method is a relatively recent discipline that has quickly become a mature method, especially for structural and thermal analysis. The costs of applying this technology to everyday design tasks have been dropping, while the capabilities delivered by the method expands constantly. The method is fully capable of delivering higher quality products in a shorter design cycle with a reduced chance of field failure, provided it is applied by a capable analyst. It is also a valid indication of thorough design practices, should an unexpected litigation crop up. The finite element method is comprised of three major phases:

6.1.1. Pre-Processing

In pre-processing the analyst develops a finite element mesh to divide the subject geometry into sub-domains for mathematical analysis, and applies material properties and boundary conditions. The goals of pre-processing are to develop an appropriate finite element mesh, assign suitable material properties, and apply boundary conditions in the form of restraints and loads.

6.1.2. Solution

During solution, the program derives the governing matrix equations from the model and solves for the primary quantities. The governing equations are assembled into matrix form and are solved numerically. The assembly process depends not only on the type of analysis but also on the model's element types and properties, material properties and boundary conditions.

6.1.3. Post-Processing

In post-processing the analyst checks the validity of the solution, examines the values of primary quantities (such as displacements and stresses), and derives and examines additional quantities. This activity is known as the post-processing phase of the finite element method.

6.2. Simulation Software: ANSYS

ANSYS, Inc. is a Computer-aided engineering software developer. Ansys publishes engineering analysis software across a range of disciplines including finite element analysis, structural analysis, computational fluid dynamics, explicit and implicit methods, and heat transfer. Thermal analysis will be done on this software which will give the temperature distribution and the heat flux. This will be given as an input for the Structural analysis, which calculates the stresses and the deformation. System requirements for Ansys are:

1. Microsoft Windows 7/8/8.1/10 Operating System
2. RAM: 4GB or above
3. Disk space: 20GB
4. Additional disk space: 30GB

6.3. Boundary Conditions:

6.3.1. Steady-State Thermal [13],

- Temperature of 150ºC on the outer surfaces of the flange couplings
- Ambient air temperature 30ºC and heat transfer rate of 25 W/m^{2}K on the outer surface of the manifold.
- Flue gases temperature 500 ºC and heat transfer rate of 70 W/m^{2}K on the inner surface of the manifold.

6.3.2. Static Structural [13],

- Pressure of 150 KPa on the inner surface of manifold along the **Z-component** while providing the **X-component** and **Y-component** with 0 KPa.
- Select the outer faces of the flange couplings and provide fixed support to them, thus making the entire structure fixed.

6.4. Simulation results Using ANSYS: Analysis of Single cylinder engine Exhaust Manifold

6.4.1. For grey cast iron

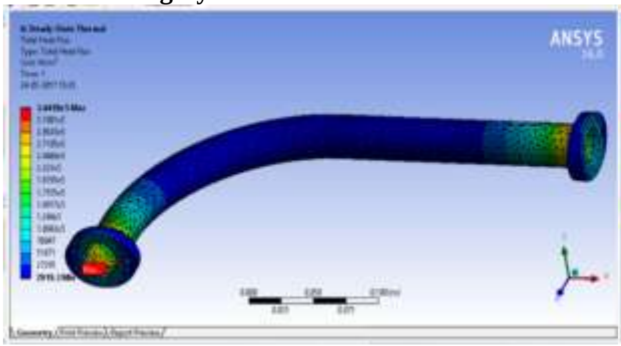


Figure 5a. Total Heat Flux

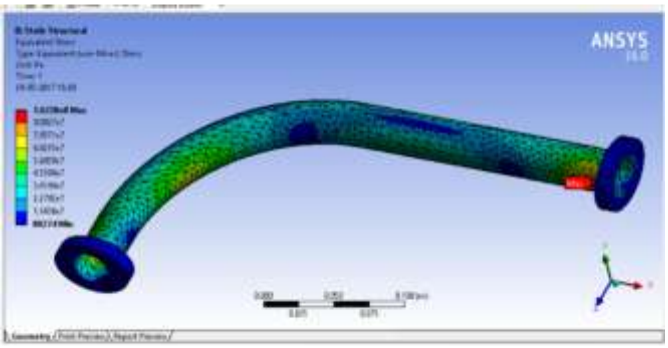


Figure 5b. Equivalent (von-mises) Stress

6.4.2. For Carbon Fiber

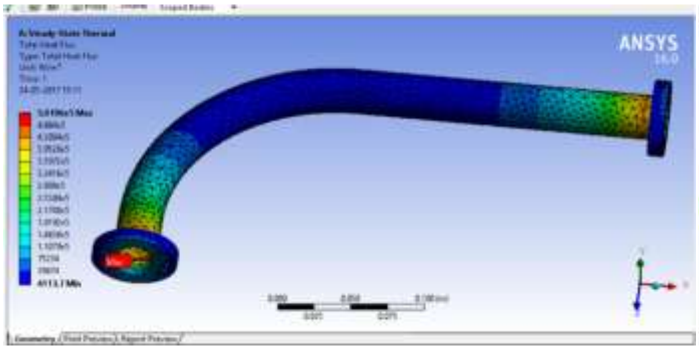


Figure 6a. Total Heat Flux

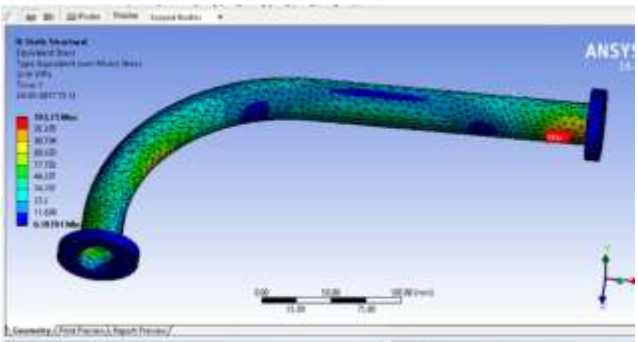


Figure 6b. Equivalent (von-mises) Stress

6.4.3. For E-Glass Epoxy

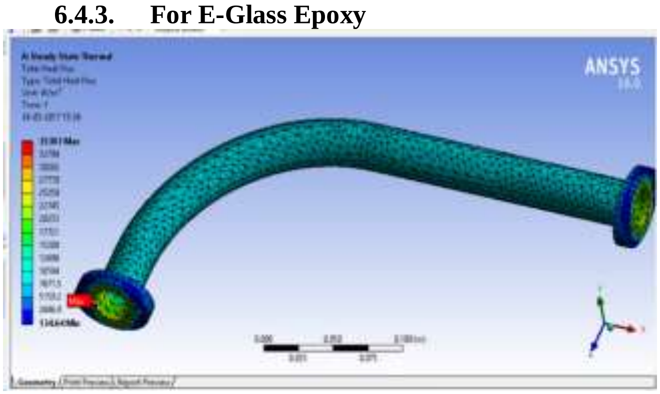


Figure 7a. Total Heat Flux

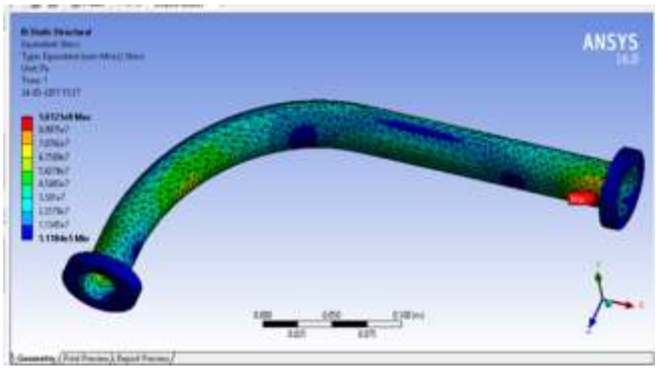


Figure 7b. Equivalent (von-mises) Stress

6.4.4. For S-Glass Epoxy

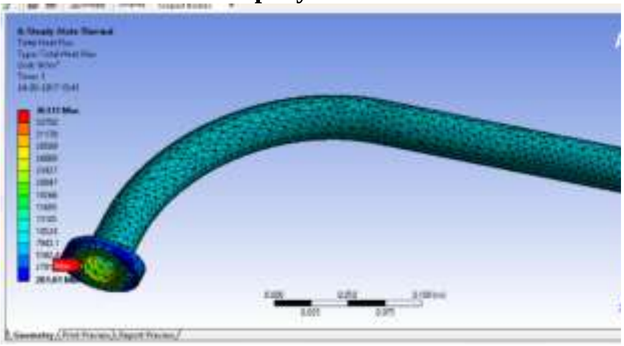


Figure 8a. Total Heat Flux

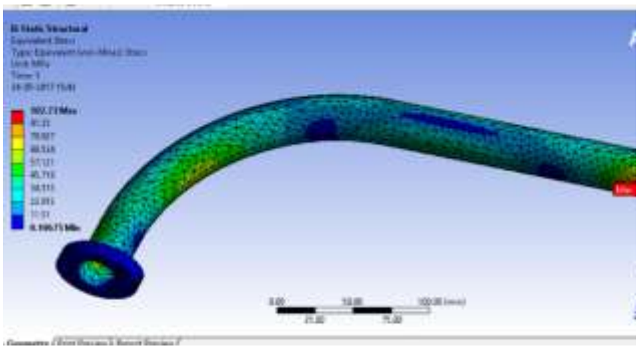


Figure 8b. Equivalent (von-mises) Stress

6.5. Simulation results Using ANSYS: Analysis of Four-cylinder engine Exhaust Manifold

6.5.1. For grey cast iron

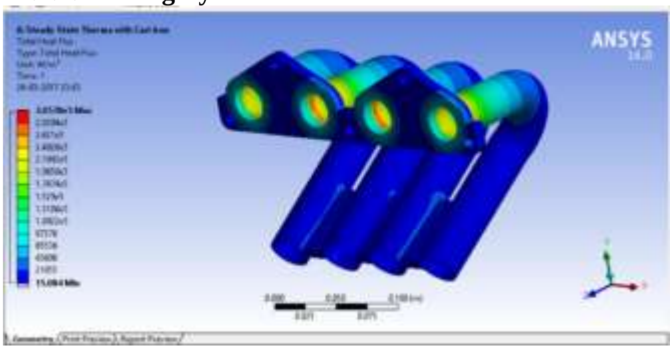


Figure 9a. Total Heat Flux

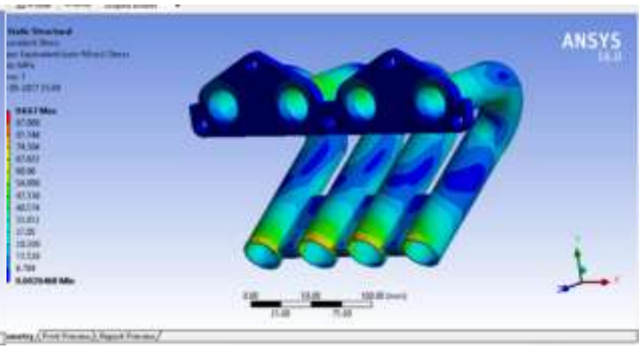


Figure 9b. Equivalent (von-mises) Stress

6.5.2. For Carbon Fiber

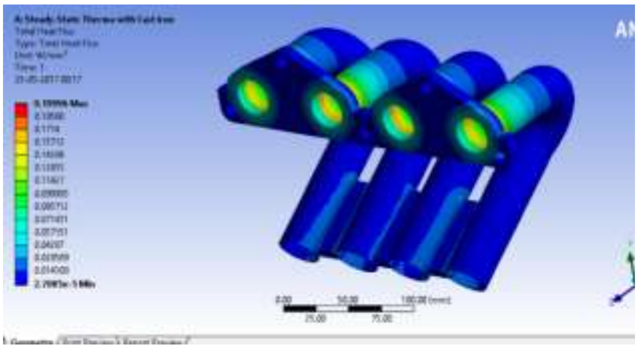


Figure 10a. Total Heat Flux

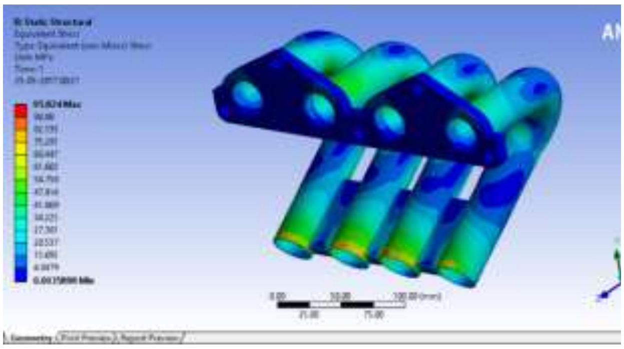


Figure 10b. Equivalent (von-mises) Stress

6.5.3. For E-Glass Epoxy

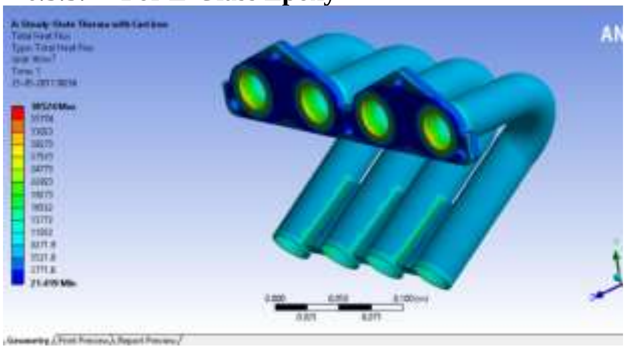


Figure 11a. Total Heat Flux

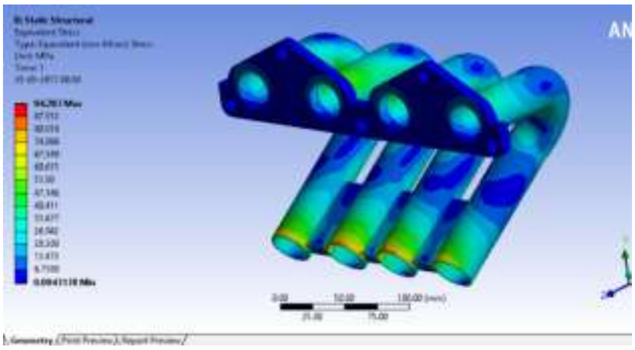


Figure 11b. Equivalent (von-mises) Stress

6.5.4. For S-Glass Epoxy

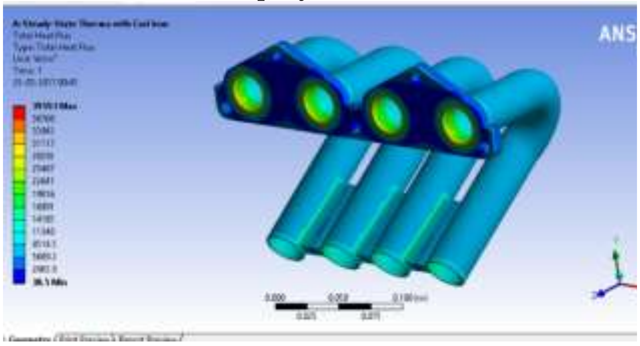


Figure 12a. Total Heat Flux

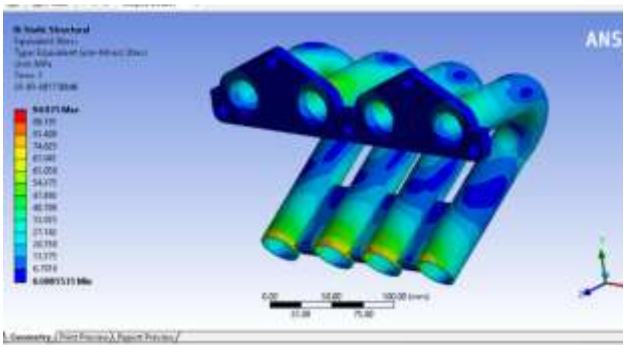


Figure 12b. Equivalent (von-mises) Stress

The results of simulations of steady state thermal and static structural are mention in a tabulated form

Table 10. Results obtained using Ansys

Sr. No.	Material	Heat flux (W/mm^2)		Stress (MPa)		Weight (Kg)
		Max.	Min.	Max	Min.	
Single cylinder exhaust manifold						
1	Carbon fiber	$5x10^5$	4113.7	103.7	0.197	0.13234
2	Cast-iron	$3.44x10^5$	2919.3	102.28	0.0802	0.61827
3	E-glass	$0.35x10^5$	134.64	101.21	0.112	0.22343
4	S-glass	$0.36x10^5$	201.01	102.73	0.106	0.1882
Four-cylinder exhaust manifold						
1	Carbon fiber	$2.05x10^5$	28.64	94.69	0.0052	0.621
2	Cast-iron	$3.06x10^5$	15.08	94.67	0.002	2.9127
3	E-glass	$0.38x10^5$	21.42	94.29	0.004	1.048
4	S-glass	$0.39x10^5$	38.5	94.9	0.008	1.1285

VII. CONCLUSION

From the result calibration, it is observed that weight of manifold is decreasing 66.67% to 75% of the weight of cast iron manifold. Also, the stresses calculated and that obtained after simulation shows that stresses are within range of the 3 composites selected. Carbon fiber shows much favorable results having 75% weight reduction and higher FOS.

Carbon fiber has higher value of heat flux which may increase heat transfer from flue gases to atmosphere, due to which temperature of flue gas reduces and which may affect performance of catalytic converter adversely. But all materials are having nearly same range of maximum and minimum value of thermal stress. Therefore, the carbon fiber which is light in weight is better to use where low weight is prime concern.

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